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## The Relation between Two Methods of Estimating Defoliation caused by Douglas-fir Tussock Moth

# The relation between two methods of estimating defoliation caused by Douglas-fir tussock moth

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## Background

The combined Stand Prognosis and Douglas-fir tussock moth (DFTM) outbreak model simulates DFTM population dynamics and defoliation on midcrown branches, translates midcrown branch defoliation to whole tree defoliation, and then predicts the effects of whole tree defoliation on tree growth and mortality. Previous analyses of this model have shown that midcrown branch defoliation is an inherently poor predictor of whole tree defoliation and that the model is very sensitive to this relation (Monserud and Crookston 1982, Gillespie et al.[7]). This problem could be addressed by expanding the existing population dynamics portion of the DFTM outbreak model to include additional crown levels, but that approach would require major revisions to the current model. An alternative approach was selected: to use a damage model that takes defoliation patterns provided by the user and predicts the resulting changes in tree growth and mortality. This damage model was developed for the western spruce budworm (Crookston 1991, Crookston and others 1990).

The WSB damage model requires estimates of missing foliage biomass by tree species, size class, crown third, and foliage age class. Most previous studies of DFTM, however, measured "total tree defoliation", which can not readily be converted to missing biomass estimates. This report summarizes analyses aimed at translating the estimates of total tree defoliation into estimates of missing biomass.

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[7] Gillespie, Andrew J.R.; David, Lance; Thompson, Matt. Preliminary report on attempts to modify the branch-tree defoliation relationship of the Douglas-fir tussock moth model. Unpublished report, 18 pages, June 1990.

## Objective

Quantify the relation between two methods of estimating defoliation: **total tree defoliation**, which estimates the percent of a tree's crown that is totally defoliated (used in previous DFTM impact studies), and **missing biomass**, which estimates the percent of foliage biomass that is missing for a given crown third and foliage age class.

## Methods

General Location -- Two study areas were used: one on the Wallowa-Whitman NF in Oregon, and the other on the Boise NF in Idaho.

All Oregon plots were in a 4,000 acre portion of the Pine RD, Wallowa-Whitman NF, that was not treated during a 1991 DFTM suppression project. Five long-term plots previously established by Wickman and Mason were used (Fish Lake plots E, F, and G, Clarks Creek, and Gate Plot E). Six additional temporary plots (FPM1-FPM6) were established for this study at sites that had relatively high tussock moth populations when sampled earlier in 1991 (as check areas for a suppresion project). Although portions of the study area had been recently defoliated by DFTM and/or western spruce budworm, DFTM was the primary defoliator in this study area in 1991.

In Idaho, trees were sampled from three areas located near previously established impact plots. On the Emmett Ranger District, Boise National Forest, two areas in the Third Creek Drainage of Squaw Creek were sampled. These areas were heavily defoliated in 1991. On the Mountain Home Ranger District, Boise National Forest, one area in the Elk Creek Drainage was sampled. Moderate to heavy defoliation was first detected in this area in 1990. This area was heavily defoliated in 1991.

Dates -- Trees in the Oregon study area were rated for defolation during either August 27-29, 1991 or April 28-29, 1992. Trees in the Idaho study area were rated on May 12-13, 1992. Data collected in April and May of 1992 regarded defoliation that occurred in 1991.

Tree selection -- On the permanent Wickman/Mason plots in Oregon, all host trees greater than 2.0 inches d.b.h. on 0.10 acre circular plots were rated.

For the newly-established plots in Oregon, host trees were stratified by host tree species (Douglas-fir or grand fir) and size class (0-7m, 7-14m, or 14+m). Starting from the northern edge of the plot and working clockwise, the first 10 trees in each species/size class category that were appropriate sample trees were rated for each plot. Trees that were within 100' of the plot center, at least 100' from the nearest road, not severely affected by competing trees (as a guideline, the crown ratio of a sample tree should be 30% or greater), and at least 1" in diameter at breast height were considered appropriate sample trees.

In Idaho, 50 to 75 trees per area were selected as sample trees. These trees had relatively full crowns (>30% crown ratio) and were classified into one of the three size classes (0-7m, 7-14m, or 14+m). Very few small trees (0-7m) were found in these areas, and when found, few met the selection criteria.

*Estimating defoliation -- Each tree was rated for defoliation using two methods. For the* ***total tree defoliation*** *(TTD) rating, each observer recorded one defoliation rating per tree; possible defoliation ratings were: 0%, 10%, 25%, 50%, 75%, 90%, or 100% (Wickman 1979). For the* ***missing biomass*** *(MB) rating, each observer will record six estimates per tree: missing new (=current) biomass and total missing biomass for each crown third. Missing biomass was rated on a scale of 0 to 9; on this scale, 0 was assigned when 0-10 percent of the foliage was missing, 1 was assigned when 11-20% of the foliage was missing, and so on. For the analyses, missing biomass ratings were transformed using two different methods, as follows:*

*(1)* ***original transformation****: (missing biomass)*10 + 5, so that the transformed ratings ranged from 5 to 95.*

*(2)* ***adjusted transformation****: (missing biomass)*11.1, so that the transformed ratings ranged from 0 to 99.9.*

*The original transformation was chosen so that the transformed ratings represented the midpoint of each defoliation category. All estimates of total missing biomass were converted to percent defoliation using this original transformation. However, concerns were raised about the resulting range of defoliation ratings (5-95%): many people would expect to see defoliation values that ranged from 0 to 100%, particularly for new foliage. The adjusted transformation was designed to obtain defoliation ratings that range from 0 to 99.9%. Two estimates of percent defoliation for new foliage were calculated for each observation, using the original and the adjusted transformation.*

*In Oregon, each tree was rated by two observers for TTD and by three other observers for MB. In Idaho, each tree was rated by one observer for TTD (one of the individuals who also rated Oregon trees for TTD) and by two other observers for MB. For trees rated by more than one observer, the average rating was used in these analyses.*

*Determining tree size category -- Tree size class (0-7m, 7-14m, or 14+m) was not recorded for trees from the five long-term plots established by Wickman and Mason in Oregon. However, diameter at breast height (dbh) was recorded for all trees. We therefore used the relation between dbh and size class observed for the temporary FPM plots in Oregon to assign size classes to trees in the long-term Oregon plots.*

*To quantify the relation between dbh and size class for trees in the temporary FPM plots, we first calculated the mean dbh and standard deviation by tree species and size class (table 1). We examined the ranges initially determined by the means plus or minus one standard deviation, and found no overlap among size classes for either species. The final boundaries were set to the midpoints separating the initial ranges (table 1). These species-specific dbh ranges correctly classified 84% of the trees from the Oregon FPM plots (table 2). We used the ranges shown in table 1 to classify the tree size category for trees in the Wickman and Mason long-term plots.*

## Results

Number of trees sampled -- Tables 3 to 5 show the number of trees sampled by defoliation rating method and by study area. In general, trees from the Oregon study area were lightly to moderately defoliated, while those from Idaho were moderately to heavily defoliated. Nearly all of the small trees sampled were located in Oregon. Idaho sample trees included grand fir (46%), Douglas-fir (36%), and subalpine fir (18%), while the Oregon trees were primarily grand fir (90%) with some Douglas-fir (10%).

Relation between TTD and MB -- Total tree defoliation versus total missing biomass is shown for each crown third for all species and size classes combined (figures 1-3), by species (figures 4-12), and by size class (figures 13-21). The relation between missing biomass and total tree defoliation was analyzed separately for each crown third.

Multiple regression was used to predict missing biomass as a function of total tree defoliation, tree species, and tree size class (the latter two variables represented by dummy variables). Species and size class contributed very little to the regression model (table 6). The proportion of the total variance accounted for ($R^2$) by the simple regression model ranged from .66 in the lower crown third to .35 in the top crown third (table 6). Transforming total tree defoliation to the natural log scale improved the model fit somewhat for the top crown third, but decreased model fit in the other two crown thirds (table 6).

Non-linear regression using Marquardt's method was also performed to fit a three parameter negative exponential equation to data from each crown third (table 7). For the top and middle crown thirds, the non-linear model explained more of the observed variation than did the linear model, as measured by a lower residual mean squares (table 8). Equations fit by species or by size class generally fell within the 95% confidence intervals for the equation fit to all trees (figures 22-25). This non-linear procedure was unable to fit the equation to data from the lower crown third.

New vs Total Missing Biomass -- The Damage Model uses four foliage age classes: new (=current) foliage, 1-year-old foliage, 2-year-old foliage, and remaining other foliage. The previous section examined the relation between total missing biomass and total tree defoliation within a given crown third. The next step was to determine the relation between total missing biomass and new missing biomass. Once the total missing biomass and new missing biomass are known for a crown third, the missing biomass for older foliage can be calculated by assuming that all older age classes are equally defoliated and that the ratio of new to older foliage is known.

Simple linear regression of new missing biomass and total tree defoliation explained very little of the observed variance -- $R^2$ values were all less than 0.2 for all crown thirds. Simple regression of new missing biomass to total missing biomass also resulted in low $R^2$ values for all crown thirds (all less than 0.32). Converting the total missing biomass to a natural log scale increased the $R^2$ values to .57 (top third), .53 (middle third), and .51 (bottom third).

Most of the crown thirds with heavy total defoliation had new missing biomass rated at the maximum rating possible (figures 26-28). Field observations

*confirm that tussock moth larvae usually consume all of the available new foliage first, and then begin feeding on older foliage (Wickman and others 1981). As an alternative to fitting one line to all total missing biomass observations, we separated the total missing biomass observations into two ranges (light to moderate and heavy), used linear regression to relate new to total missing biomass for the light-moderate category, and assigned the maximum defoliation rating to new missing biomass for the heavy category.*

*For each crown third, we tested a range of different cut-off points for separating the two categories, and selected the point that resulted in the highest $R^2$ value for the linear regression, subject to the condition that at least three quarters of the non-maximum new missing biomass observations had to be included in the light-moderate category. The optimum cut-off points for separating total missing biomass into the two ranges varied with crown third (tables 9 and 10). The proportion of new missing biomass observations above the cut-off point that were at the maximum was .96 in the top crown third, .86 in the middle third, and .79 in the bottom third. The sums of squares attributable to error was less when the observations were partitioned into two total missing biomass categories than when all observations were combined (tables 9 and 10).*

*If total missing biomass, new missing biomass, and the ratio of new to older foliage are known, then missing biomass for older foliage can be calculated. Unfortunately, most of what is known about the ratio of new to old foliage for DFTM host trees is based on a study of one codominant Douglas-fir (Crookston 1991, summarized in table 11). Further, in some cases the observations that we recorded do not fit the reported new-to-old foliage ratios very well; for example, sometimes the observed new missing biomass was so large (relative to the reported ratio of new to old foliage) that even if no older foliage was defoliated, the observed total missing biomass was -- in theory -- impossibly low. These discrepancies could result from inaccurate foliage ratios (after all, they were based on just one tree!) or errors in our field estimates of new and total missing biomass.*

*We recommend that when the calculated missing biomass values conflict with the new-to-old foliage ratios summarized in table 11, the new missing biomass value should be used and the older missing biomass value should be set to zero (in effect, ignoring the reported foliage ratios); otherwise, use the foliage ratios to calculate missing biomass for older foliage, treating all older foliage age classes equally. This approach makes the following assumptions: that the field estimates of new and total missing biomass are more reliable than the foliage ratios reported for the single Douglas-fir, that tussock moth larvae consume all new foliage first and then switch to older foliage, and that larvae do not discriminate among age classes of older foliage.*

## Recommendations

*To convert total tree defoliation (TTD) ratings for individual trees to missing biomass (MB) ratings, complete the following steps:*

(1) Convert TTD to total MB as follows (tables 6 and 7):

top crown third: $Total\ MB = 96.92 * (1 - (.7723 * e^{(-.06767 * TTD)}))$

middle crown third: $Total\ MB = 98.72 * (1 - (.8416 * e^{(-.02695 * TTD)}))$

bottom crown third: $Total\ MB = 15.66 + (.7405 * TTD)$

(2) Convert total MB to new MB as follows (tables 9 and 10):

(a) if total MB is above the cut-off point for the crown third (see table 9), set new MB to the maximum value (95% for the original transformation, or 99.9% for the adjusted transformation)

(b) if total MB is below the cut-off point for the crown third, then calculate new MB as follows:

***original transformation:***

top third: $New\ MB = -51.595 + (41.203 * \ln(total\ MB))$

middle third: $New\ MB = -29.182 + (35.264 * \ln(total\ MB))$

bottom third: $New\ MB = -45.594 + (41.554 * \ln(total\ MB))$

***adjusted transformation:***

top third: $New\ MB = -62.818 + (45.735 * \ln(total\ MB))$

middle third: $New\ MB = -37.940 + (39.142 * \ln(total\ MB))$

bottom third: $New\ MB = -56.155 + (46.124 * \ln(total\ MB))$

(3) Calculate older MB from new MB, total MB, and the proportions of new and older foliage by crown third and tree size class (table 10) as follows:

$total\ MB = (proportion\ new * new\ MB) + (proportion\ older * older\ MB)$

$[A] = [B] + [C]$

If [B] is greater than or equal to [A], set older MB to zero;

otherwise, $older\ MB = \frac{[A] - [B]}{proportion\ older}$

***Summary***

*The relation between two measures of defoliation was analyzed for a dataset that includes lightly to moderately defoliated trees from Oregon and heavily defoliated trees from Idaho. Very little of the observed variation could be attributed to differences among tree species or tree size classes. Two procedures for converted total tree biomass estimates to missing biomass estimates are described in the previous section: the original transformation results in missing biomass estimates that range from 5% to 95%, while the adjusted transformation produces estimates that range from 0% to 99.9%.*

***References***

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*Wickman, B.E. 1979. How to estimate defoliation and predict tree damage. Agric. Handb. 550. U.S. Department of Agriculture. 15 p.*

*Table 1. Diameter at breast height (dbh) observations for trees in Oregon FPM temporary plots, and dbh ranges used to assign tree size classes for trees in long-term Oregon plots.*

| species | size class | no. trees | mean dbh (in.) | stand. dev. (in.) | smallest tree (in.) | largest tree (in.) | final range lower (in.) | final range upper (in.) |
|---|---|---|---|---|---|---|---|---|
| GF | S | 59 | 4.32 | 2.31 | 2.0 | 7.6 | --- | 5.7 |
| | M | 59 | 8.09 | 2.28 | 4.1 | 13.4 | 5.8 | 11.3 |
| | L | 58 | 18.04 | 5.72 | 8.7 | 37.8 | 11.4 | --- |
| DF | S | 4 | 4.03 | 1.47 | 2.0 | 5.2 | --- | 6.1 |
| | M | 7 | 9.29 | 2.67 | 5.5 | 12.3 | 6.2 | 12.1 |
| | L | 19 | 23.85 | 11.45 | 10.1 | 59.2 | 12.2 | --- |

*Table 2. Results of assigning size class to trees in Oregon FPM temporary plots based on dbh ranges shown in table 1.*

| species | size class | no. trees | no. of trees classified: too small | correctly | too large |
|---|---|---|---|---|---|
| GF | S | 59 | 0 | 52 | 7 |
| | M | 59 | 9 | 43 | 7 |
| | L | 58 | 5 | 53 | 0 |
| DF | S | 4 | 0 | 4 | 0 |
| | M | 7 | 1 | 4 | 2 |
| | L | 19 | 1 | 18 | 0 |
| Total: | | 206 | 16 (8%) | 174 (84%) | 16 (8%) |

Table 3. Number of trees sampled by Total Tree Defoliation category.

| | no. trees | Total Tree Defoliation Rating 0-20% | 21-40% | 41-60% | 61-80% | 81-100% |
|---|---|---|---|---|---|---|
| OREGON + IDAHO | | | | | | |
| all trees | 768 | 501 | 116 | 71 | 37 | 43 |
| Douglas-fir | 126 | 58 | 22 | 20 | 10 | 16 |
| grand fir | 606 | 440 | 88 | 44 | 20 | 14 |
| subalpine fir | 36 | 3 | 6 | 7 | 7 | 13 |
| large trees | 351 | 228 | 54 | 34 | 21 | 14 |
| medium trees | 261 | 146 | 42 | 30 | 16 | 27 |
| small trees | 156 | 127 | 20 | 7 | 0 | 2 |
| DF - large | 75 | 37 | 16 | 11 | 7 | 4 |
| DF - medium | 42 | 14 | 4 | 9 | 3 | 12 |
| DF - small | 9 | 7 | 2 | 0 | 0 | 0 |
| GF - large | 257 | 188 | 32 | 20 | 11 | 6 |
| GF - medium | 203 | 132 | 38 | 17 | 9 | 7 |
| GF - small | 146 | 120 | 18 | 7 | 0 | 1 |
| SAF - large | 19 | 3 | 6 | 3 | 3 | 4 |
| SAF - medium | 16 | 0 | 0 | 4 | 4 | 8 |
| SAF - small | 1 | 0 | 0 | 0 | 0 | 1 |
| OREGON only | | | | | | |
| all trees | 572 | 478 | 80 | 11 | 3 | 0 |
| Douglas-fir | 56 | 45 | 9 | 0 | 2 | 0 |
| grand fir | 516 | 433 | 71 | 11 | 1 | 0 |
| large trees | 242 | 207 | 31 | 2 | 2 | 0 |
| medium trees | 179 | 144 | 31 | 3 | 1 | 0 |
| small trees | 151 | 127 | 18 | 6 | 0 | 0 |
| DF - large | 32 | 25 | 5 | 0 | 2 | 0 |
| DF - medium | 15 | 13 | 2 | 0 | 0 | 0 |
| DF - small | 9 | 7 | 2 | 0 | 0 | 0 |
| GF - large | 210 | 182 | 26 | 2 | 0 | 0 |
| GF - medium | 164 | 131 | 29 | 3 | 1 | 0 |
| GF - small | 142 | 120 | 16 | 6 | 0 | 0 |

*Table 3, continued.*

| | no. trees | Total Tree Defoliation Rating 0-20% | 21-40% | 41-60% | 61-80% | 81-100% |
|---|---|---|---|---|---|---|
| *IDAHO only* | | | | | | |
| all trees | 196 | 23 | 36 | 60 | 34 | 43 |
| Douglas-fir | 70 | 13 | 13 | 20 | 8 | 16 |
| grand fir | 90 | 7 | 17 | 33 | 19 | 14 |
| subalpine fir | 36 | 3 | 6 | 7 | 7 | 13 |
| large trees | 109 | 21 | 23 | 32 | 19 | 14 |
| medium trees | 82 | 2 | 11 | 27 | 15 | 27 |
| small trees | 5 | 0 | 2 | 1 | 0 | 2 |
| DF - large | 43 | 12 | 11 | 11 | 5 | 4 |
| DF - medium | 27 | 1 | 2 | 9 | 3 | 12 |
| DF - small | 0 | 0 | 0 | 0 | 0 | 0 |
| GF - large | 47 | 6 | 6 | 18 | 11 | 6 |
| GF - medium | 39 | 1 | 9 | 14 | 8 | 7 |
| GF - small | 4 | 0 | 2 | 1 | 0 | 1 |
| SAF - large | 19 | 3 | 6 | 3 | 3 | 4 |
| SAF - medium | 16 | 0 | 0 | 4 | 4 | 8 |
| SAF - small | 1 | 0 | 0 | 0 | 0 | 1 |

Table 4. Number of trees sampled by Missing Biomass[1] category (original scale, range = 5 - 95%).

| | no. trees | Missing Biomass Rating 0-20% | 21-40% | 41-60% | 61-80% | 81-100% |
|---|---|---|---|---|---|---|
| IDAHO + OREGON | | | | | | |
| all trees | 768 | 187 | 220 | 176 | 99 | 86 |
| Douglas-fir | 126 | 21 | 23 | 24 | 16 | 42 |
| grand fir | 606 | 165 | 194 | 148 | 71 | 28 |
| subalpine fir | 36 | 1 | 3 | 4 | 12 | 16 |
| large trees | 351 | 70 | 107 | 94 | 47 | 33 |
| medium trees | 261 | 55 | 63 | 56 | 41 | 46 |
| small trees | 156 | 62 | 50 | 26 | 11 | 7 |
| DF - large | 75 | 16 | 14 | 19 | 9 | 17 |
| DF - medium | 42 | 5 | 3 | 5 | 6 | 23 |
| DF - small | 9 | 0 | 6 | 0 | 1 | 2 |
| GF - large | 257 | 53 | 90 | 72 | 31 | 11 |
| GF - medium | 203 | 50 | 60 | 50 | 30 | 13 |
| GF - small | 146 | 62 | 44 | 26 | 10 | 4 |
| SAF - large | 19 | 1 | 3 | 3 | 7 | 5 |
| SAF - medium | 16 | 0 | 0 | 1 | 5 | 10 |
| SAF - small | 1 | 0 | 0 | 0 | 0 | 1 |
| OREGON only | | | | | | |
| all trees | 572 | 182 | 198 | 145 | 36 | 11 |
| Douglas-fir | 56 | 17 | 15 | 11 | 7 | 6 |
| grand fir | 516 | 165 | 183 | 134 | 29 | 5 |
| large trees | 242 | 65 | 90 | 71 | 11 | 5 |
| medium trees | 179 | 55 | 58 | 49 | 15 | 2 |
| small trees | 151 | 62 | 50 | 25 | 10 | 4 |
| DF - large | 32 | 12 | 7 | 7 | 2 | 4 |
| DF - medium | 15 | 5 | 2 | 4 | 4 | 0 |
| DF - small | 9 | 0 | 6 | 0 | 1 | 2 |
| GF - large | 210 | 53 | 83 | 64 | 9 | 1 |
| GF - medium | 164 | 50 | 56 | 45 | 11 | 2 |
| GF - small | 142 | 62 | 44 | 25 | 9 | 2 |

[1] for small trees, missing biomass rating = .06*tmb + .27*mmb + .67*bmb
for other trees, missing biomass rating = .12*tmb + .47*mmb + .41*bmb
tmb = total missing biomass for the top third,
mmb = total missing biomass for the middle third,
bmb = total missing biomass for the bottom third.
Values for relative biomass by crown thirds and tree size are from Crookston (1991).

Table 4, continued.

| | no. trees | Missing Biomass Rating 0-20% | 21-40% | 41-60% | 61-80% | 81-100% |
|---|---|---|---|---|---|---|
| IDAHO only | | | | | | |
| all trees | 196 | 5 | 22 | 31 | 63 | 75 |
| Douglas-fir | 70 | 4 | 8 | 13 | 9 | 36 |
| grand fir | 90 | 0 | 11 | 14 | 42 | 23 |
| subalpine fir | 36 | 1 | 3 | 4 | 12 | 16 |
| large trees | 109 | 5 | 17 | 23 | 36 | 28 |
| medium trees | 82 | 0 | 5 | 7 | 26 | 44 |
| small trees | 5 | 0 | 0 | 1 | 1 | 3 |
| DF - large | 43 | 4 | 7 | 12 | 7 | 13 |
| DF - medium | 27 | 0 | 1 | 1 | 2 | 23 |
| DF - small | 0 | 0 | 0 | 0 | 0 | 0 |
| GF - large | 47 | 0 | 7 | 8 | 22 | 10 |
| GF - medium | 39 | 0 | 4 | 5 | 19 | 11 |
| GF - small | 4 | 0 | 0 | 1 | 1 | 2 |
| SAF - large | 19 | 1 | 3 | 3 | 7 | 5 |
| SAF - medium | 16 | 0 | 0 | 1 | 5 | 10 |
| SAF - small | 1 | 0 | 0 | 0 | 0 | 1 |

Table 5. Number of trees sampled by Missing Biomass[1] category (adjusted scale, range = 0 - 99.9%)

| | no. trees | Missing Biomass Rating 0-20% | 21-40% | 41-60% | 61-80% | 81-100% |
|---|---|---|---|---|---|---|
| IDAHO + OREGON | | | | | | |
| all trees | 768 | 146 | 247 | 195 | 101 | 79 |
| Douglas-fir | 126 | 16 | 25 | 29 | 16 | 40 |
| grand fir | 606 | 130 | 218 | 162 | 72 | 24 |
| subalpine fir | 36 | 0 | 4 | 4 | 13 | 15 |
| large trees | 351 | 54 | 117 | 102 | 47 | 31 |
| medium trees | 261 | 38 | 75 | 63 | 43 | 42 |
| small trees | 156 | 54 | 55 | 30 | 11 | 6 |
| DF - large | 75 | 14 | 14 | 21 | 10 | 16 |
| DF - medium | 42 | 2 | 5 | 7 | 6 | 22 |
| DF - small | 9 | 0 | 6 | 1 | 0 | 2 |
| GF - large | 257 | 40 | 99 | 78 | 30 | 10 |
| GF - medium | 203 | 36 | 70 | 55 | 31 | 11 |
| GF - small | 146 | 54 | 49 | 29 | 11 | 3 |
| SAF - large | 19 | 0 | 4 | 3 | 7 | 5 |
| SAF - medium | 16 | 0 | 0 | 1 | 6 | 9 |
| SAF - small | 1 | 0 | 0 | 0 | 0 | 1 |
| OREGON only | | | | | | |
| all trees | 572 | 144 | 224 | 160 | 35 | 9 |
| Douglas-fir | 56 | 14 | 17 | 14 | 5 | 6 |
| grand fir | 516 | 130 | 207 | 146 | 30 | 3 |
| large trees | 242 | 52 | 98 | 76 | 11 | 5 |
| medium trees | 179 | 38 | 71 | 55 | 14 | 1 |
| small trees | 151 | 54 | 55 | 29 | 10 | 3 |
| DF - large | 32 | 12 | 6 | 8 | 2 | 4 |
| DF - medium | 15 | 2 | 5 | 5 | 3 | 0 |
| DF - small | 9 | 0 | 6 | 1 | 0 | 2 |
| GF - large | 210 | 40 | 92 | 68 | 9 | 1 |
| GF - medium | 164 | 36 | 66 | 50 | 11 | 1 |
| GF - small | 142 | 54 | 49 | 28 | 10 | 1 |

[1] for small trees, missing biomass rating = .06*tmb + .27*mmb + .67*bmb
for other trees, missing biomass rating = .12*tmb + .47*mmb + .41*bmb
tmb = total missing biomass for the top third,
mmb = total missing biomass for the middle third,
bmb = total missing biomass for the bottom third.
Values for relative biomass by crown thirds and tree size are from Crookston (1991).

*Table 5, continued.*

| | no. trees | Missing Biomass Rating 0-20% | 21-40% | 41-60% | 61-80% | 81-100% |
|---|---|---|---|---|---|---|
| *IDAHO only* | | | | | | |
| *all trees* | 196 | 2 | 23 | 35 | 66 | 70 |
| *Douglas-fir* | 70 | 2 | 8 | 15 | 1 | 34 |
| *grand fir* | 90 | 0 | 11 | 16 | 42 | 21 |
| *subalpine fir* | 36 | 0 | 4 | 4 | 13 | 15 |
| *large trees* | 109 | 2 | 19 | 26 | 36 | 26 |
| *medium trees* | 82 | 0 | 4 | 8 | 29 | 41 |
| *small trees* | 5 | 0 | 0 | 1 | 1 | 3 |
| *DF - large* | 43 | 2 | 8 | 13 | 8 | 12 |
| *DF - medium* | 27 | 0 | 0 | 2 | 3 | 22 |
| *DF - small* | 0 | 0 | 0 | 0 | 0 | 0 |
| *GF - large* | 47 | 0 | 7 | 10 | 21 | 9 |
| *GF - medium* | 39 | 0 | 4 | 5 | 20 | 10 |
| *GF - small* | 4 | 0 | 0 | 1 | 1 | 2 |
| *SAF - large* | 19 | 0 | 4 | 3 | 7 | 5 |
| *SAF - medium* | 16 | 0 | 0 | 1 | 6 | 9 |
| *SAF - small* | 1 | 0 | 0 | 0 | 0 | 1 |

*Table 6. Results of simple and multiple regression using missing biomass as the dependent variable and total tree defoliation (TTD), tree species (sp), and/or tree size class (size) as independent variables (n=768 trees).*

| crown third | independent variables | intercept (SE) | slope (SE) | partial R2 | model R2 | F | Prob>F |
|---|---|---|---|---|---|---|---|
| top | TTD | 51.5 (1.12) | .665 (.0326) | .352 | .352 | 416.9 | 0.0001 |
| | TTD, sp | | | .003 | .355 | | |
| | TTD, sp, size | | | .002 | .357 | | |
| | ln(TTD) | | | | .516 | | |
| middle | TTD | 27.6 (0.79) | .825 (.0229) | .629 | .629 | 1296 | 0.0001 |
| | TTD, sp | | | .004 | .633 | | |
| | TTD, sp, size | | | .000 | .633 | | |
| | ln(TTD) | | | | .609 | | |
| bottom | TTD | 15.7 (.654) | .741 (.0191) | .663 | .663 | 1509 | 0.0001 |
| | TTD, sp | | | .018 | .681 | | |
| | TTD, sp, size | | | .001 | .682 | | |
| | ln(TTD) | | | | .513 | | |

*Table 7. Parameters for a negative exponential equation[1] estimated using non-linear regression.*

| crown third | parameter | estimate | asymptotic std. error | asymptotic confid. interval lower | asymptotic confid. interval upper |
|---|---|---|---|---|---|
| top | B0 | 96.92 | 1.662 | 93.65 | 100.18 |
| | B1 | 0.7723 | 0.02219 | 0.7288 | 0.8159 |
| | B2 | 0.06767 | 0.004708 | 0.05843 | 0.07691 |
| middle | B0 | 98.72 | 3.171 | 92.50 | 104.95 |
| | B1 | 0.8416 | 0.01211 | 0.8179 | 0.8654 |
| | B2 | 0.02695 | 0.002433 | 0.02217 | 0.03173 |
| bottom | ------ failed to converge ------- | | | | |

[1] $\text{Missing biomass} = B0 * (1 - [B1 * \exp^{(-B2 * \text{total tree defoliation})}])$

*Table 8. Residual mean squares for non-linear models and simple linear regressions using missing biomass as the dependent variable and total tree defoliation (TTD) or the natural log of total tree defoliation (ln(TTD)) as independent variables (n=768 trees).*

| crown third | non-linear model | linear TTD model | linear ln(TTD) model |
|---|---|---|---|
| top | 352 | 509 | 380 |
| middle | 212 | 252 | 265 |
| bottom | --- | 175 | 252 |

*Table 9. Results of simple linear regression by crown third using new missing biomass (new MB) as the dependent variable and total missing biomass (total MB) or the natural log of total missing biomass (ln(total MB)) as independent variables. New missing biomass is calculated using the **original transformation** (see page 3).*

| | new MB * total MB | | | new MB * ln(total MB) | | |
|---|---|---|---|---|---|---|
| | top | middle | bottom | top | middle | bottom |
| **all observations (n=768)** | | | | | | |
| $R^2$ | 0.32 | 0.25 | 0.23 | 0.57 | 0.53 | 0.51 |
| error sum of squares | 126,846 | 245,855 | 374,498 | 79,277 | 155,625 | 241,701 |
| intercept | 69.090 | 67.294 | 61.602 | 15.553 | 12.232 | -0.518 |
| slope | 0.313 | 0.397 | 0.537 | 18.367 | 20.271 | 24.523 |
| **optimum cut-off point** (% total missing biomass) | 42% | 39% | 32% | 42% | 39% | 32% |
| **observations below the cut-off point** | | | | | | |
| number of observations | 192 | 351 | 482 | 192 | 351 | 482 |
| $R^2$ | 0.67 | 0.47 | 0.53 | 0.79 | 0.67 | 0.65 |
| error sum of squares | 44,193 | 137,244 | 187,283 | 28,939 | 87,091 | 137,987 |
| intercept | 24.250 | 35.985 | 23.504 | -51.595 | -29.182 | -45.594 |
| slope | 2.048 | 1.727 | 2.519 | 41.203 | 35.264 | 41.554 |
| **observations above the cut-off point** | | | | | | |
| number of observations | 576 | 417 | 286 | 576 | 417 | 286 |
| % of observations that = the maximum | 95.8 | 88.5 | 78.7 | 95.8 | 88.5 | 78.7 |
| error sum of squares* | 6,614 | 19,036 | 34,486 | 6,614 | 19,036 | 34,486 |

* = sum (maximum value - observed value)$^2$

Table 10. Results of simple linear regression by crown third using new missing biomass (new MB) as the dependent variable and total missing biomass (total MB) or the natural log of total missing biomass (ln(total MB)) as independent variables. New missing biomass is calculated using the **adjusted transformation** (see page 3).

| | new MB * total MB | | | new MB * ln(total MB) | | |
|---|---|---|---|---|---|---|
| | top | middle | bottom | top | middle | bottom |
| **all observations (n=768)** | | | | | | |
| $R^2$ | 0.32 | 0.25 | 0.23 | 0.57 | 0.53 | 0.51 |
| error sum of squares | 156,283 | 302,909 | 461,397 | 97,676 | 191,740 | 297,787 |
| intercept | 71.140 | 69.147 | 62.829 | 11.715 | 8.029 | -6.123 |
| slope | 0.347 | 0.441 | 0.596 | 20.387 | 22.500 | 27.220 |
| **optimum cut-off point** (% total missing biomass) | 42% | 39% | 32% | 42% | 39% | 32% |
| **observations below the cut-off point** | | | | | | |
| number of observations | 192 | 351 | 482 | 192 | 351 | 482 |
| $R^2$ | 0.67 | 0.47 | 0.53 | 0.79 | 0.67 | 0.65 |
| error sum of squares | 54,449 | 169,093 | 230,739 | 35,655 | 107,302 | 170,008 |
| intercept | 21.369 | 34.394 | 20.541 | -62.818 | -37.940 | -56.155 |
| slope | 2.273 | 1.917 | 2.796 | 45.735 | 39.142 | 46.124 |
| **observations above the cut-off point** | | | | | | |
| number of observations | 576 | 417 | 286 | 576 | 417 | 286 |
| % of observations that = the maximum | 95.8 | 88.5 | 78.7 | 95.8 | 88.5 | 78.7 |
| error sum of squares* | 8,149 | 24,719 | 42,490 | 8,149 | 24,719 | 42,490 |

* = sum (maximum value - observed value)$^2$

Table 11. Summary of percentages of new and older foliage by tree size class and crown third (from Crookston 1991, table 9).

| | small trees | | medium & large trees | |
|---|---|---|---|---|
| crown third | new | old | new | old |
| top | 70 | 30 | 50 | 50 |
| middle | 45 | 55 | 30 | 70 |
| bottom | 35 | 65 | 10 | 90 |

***Figures***

*Figures 1-3:* *Scattergrams for total tree defoliation versus total missing biomass for **all species and all size classes combined** are shown by **crown third** (Fig. 1 - top, Fig. 2 - middle, Fig. 3 - bottom).*

*Figures 4-6:* *Scattergrams for total tree defoliation versus total missing biomass for **all size classes** in the **top crown third only** are shown **by species** (Fig. 4 - grand fir, Fig. 5 - Douglas-fir, Fig. 6 - subalpine fir).*

*Figures 7-9:* *Scattergrams for total tree defoliation versus total missing biomass for **all size classes** in the **middle crown third only** are shown **by species** (Fig. 7 - grand fir, Fig. 8 - Douglas-fir, Fig. 9 - subalpine fir).*

*Figures 10-12:* *Scattergrams for total tree defoliation versus total missing biomass for **all size classes** in the **bottom crown third only** are shown **by species** (Fig. 10 - grand fir, Fig. 11 - Douglas-fir, Fig. 12 - subalpine fir).*

*Figures 13-15:* *Scattergrams for total tree defoliation versus total missing biomass for **all species** in the **top crown third only** are shown **by size class** (Fig. 13 - large trees, Fig. 14 - medium trees, Fig. 15 - small trees).*

*Figures 16-18:* *Scattergrams for total tree defoliation versus total missing biomass for **all species** in the **middle crown third only** are shown **by size class** (Fig. 16 - large trees, Fig. 17 - medium trees, Fig. 18 - small trees).*

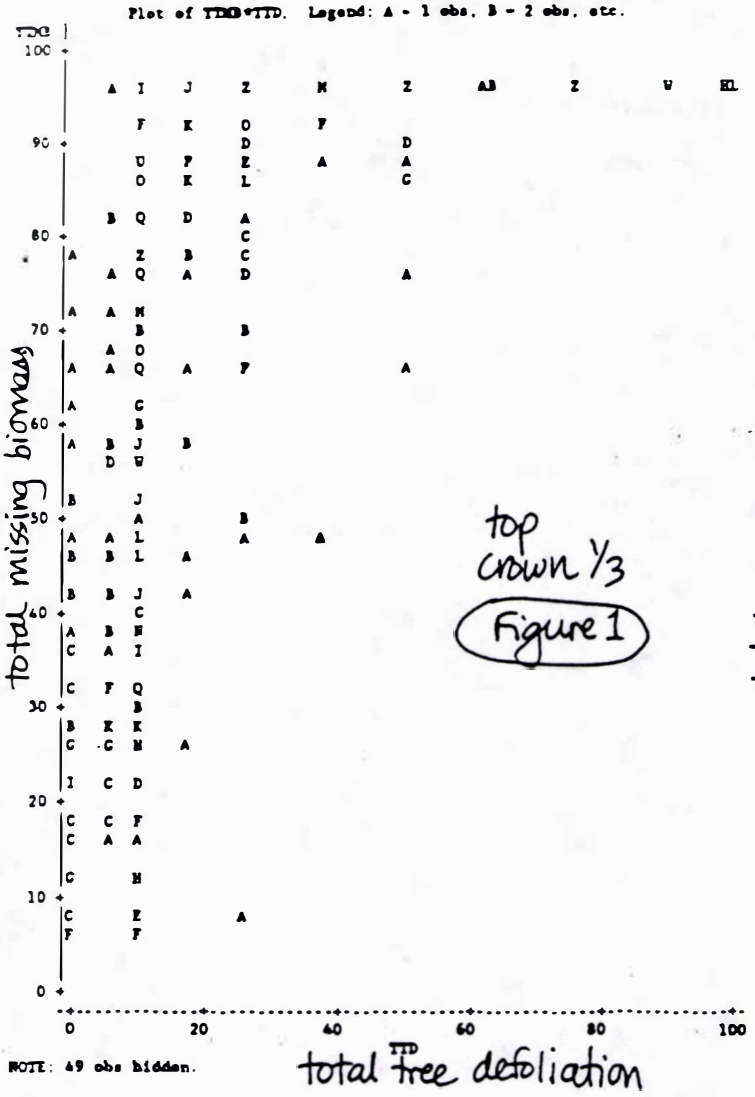
*Figures 19-21:* *Scattergrams for total tree defoliation versus total missing biomass for **all species** in the **bottom crown third only** are shown **by size class** (Fig. 19 - large trees, Fig. 20 - medium trees, Fig. 21 - small trees).*

*Figures 22-23:* *Equations fit by non-linear regression by **size class** (Fig. 22) or **species** (Fig. 23) for the **top crown third only**, including the upper and lower 95% confidence intervals.*

*Figures 24-25:* *Equations fit by non-linear regression by **size class** (Fig. 24) or **species** (Fig. 25) for the **middle crown third only**, including the upper and lower 95% confidence intervals.*

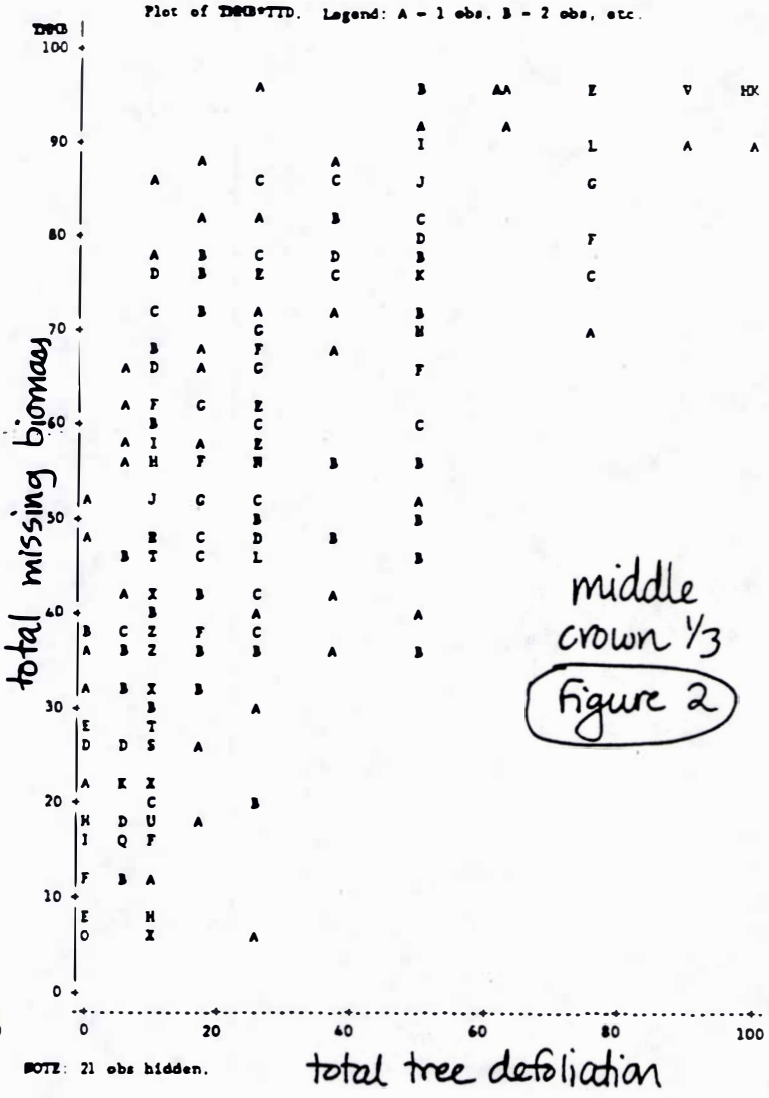
*Figures 26-28:* *Scattergrams for new missing biomass versus total missing biomass for **all species and size classes combined** are shown **by crown third** (Fig. 26 - top, Fig. 27 - middle, Fig. 28 - bottom).*

# All Trees



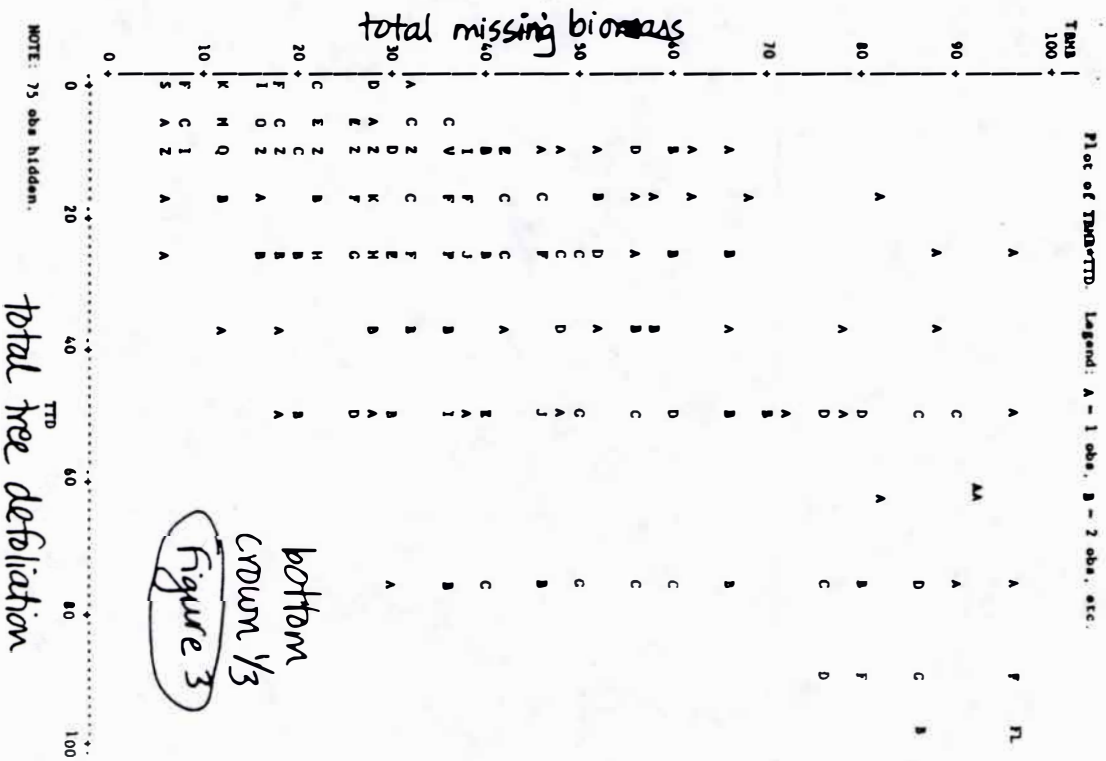

top crown 1/3

Figure 1




middle crown 1/3

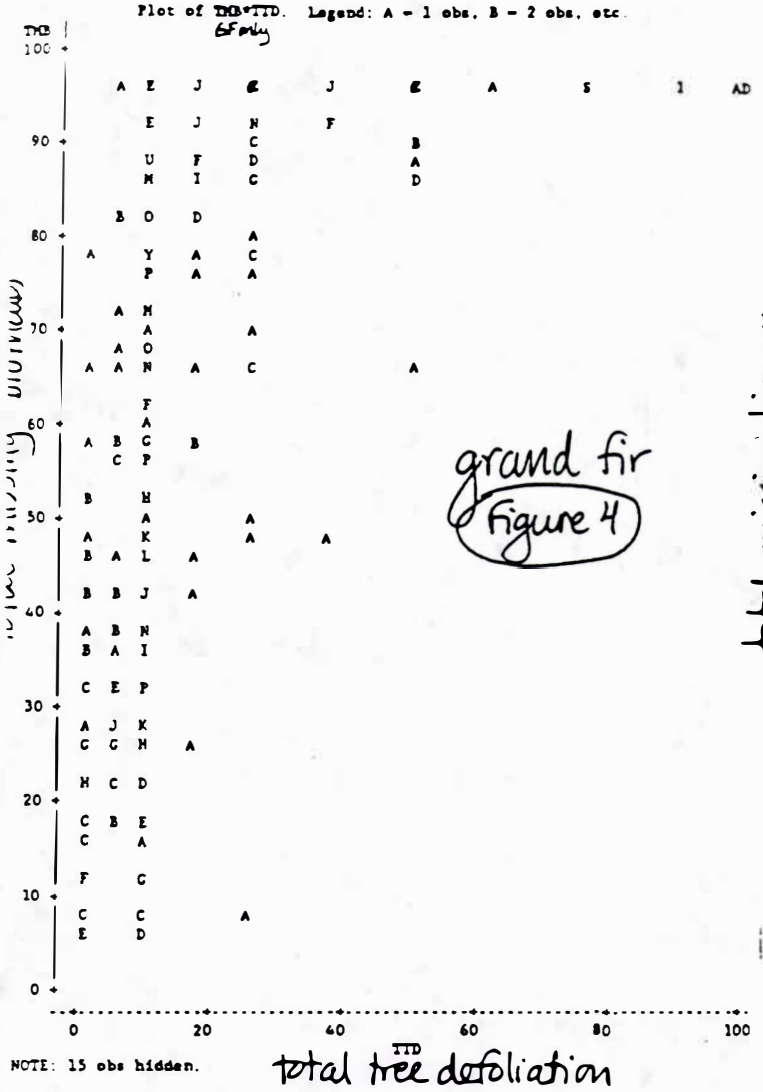
Figure 2



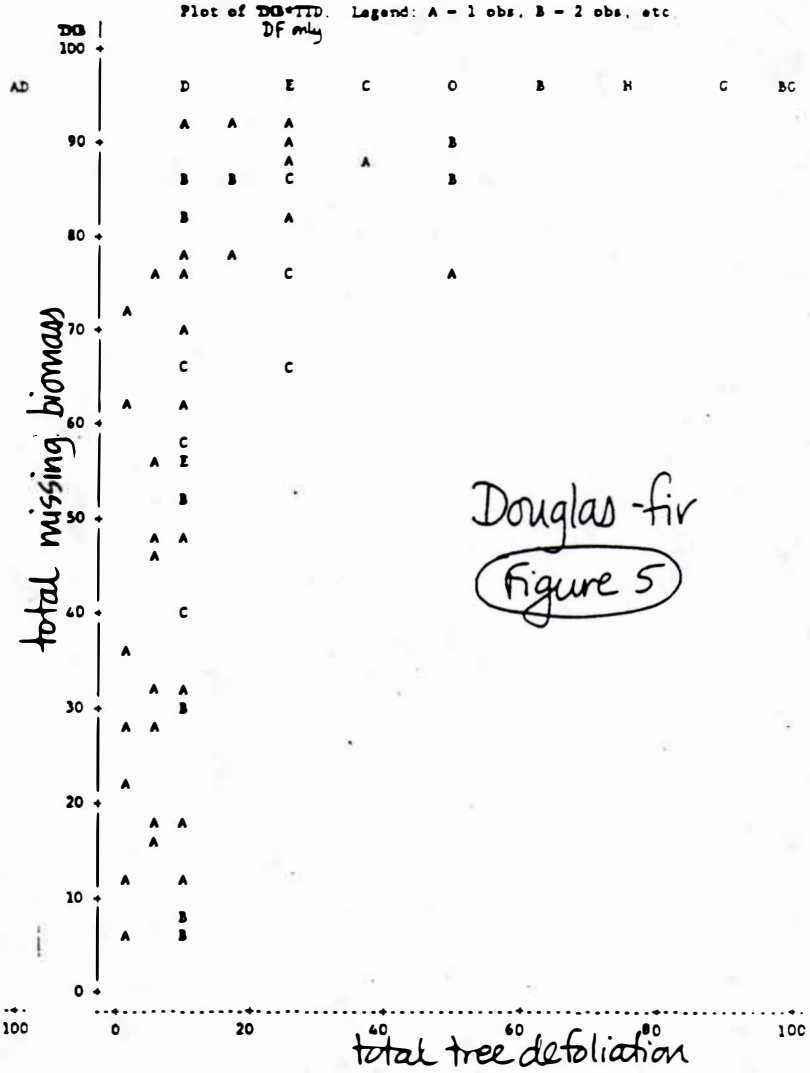

bottom crown 1/3

Figure 3

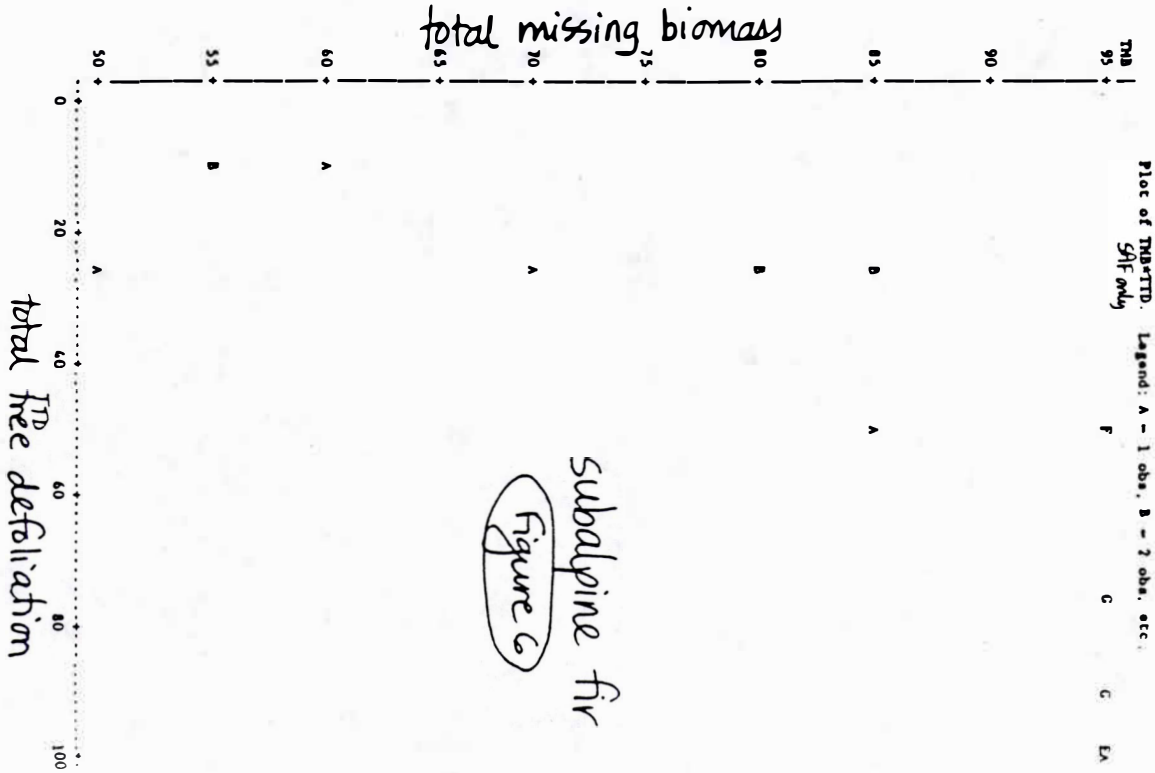
# By Species - Top Crown 1/3 Only




grand fir
Figure 4

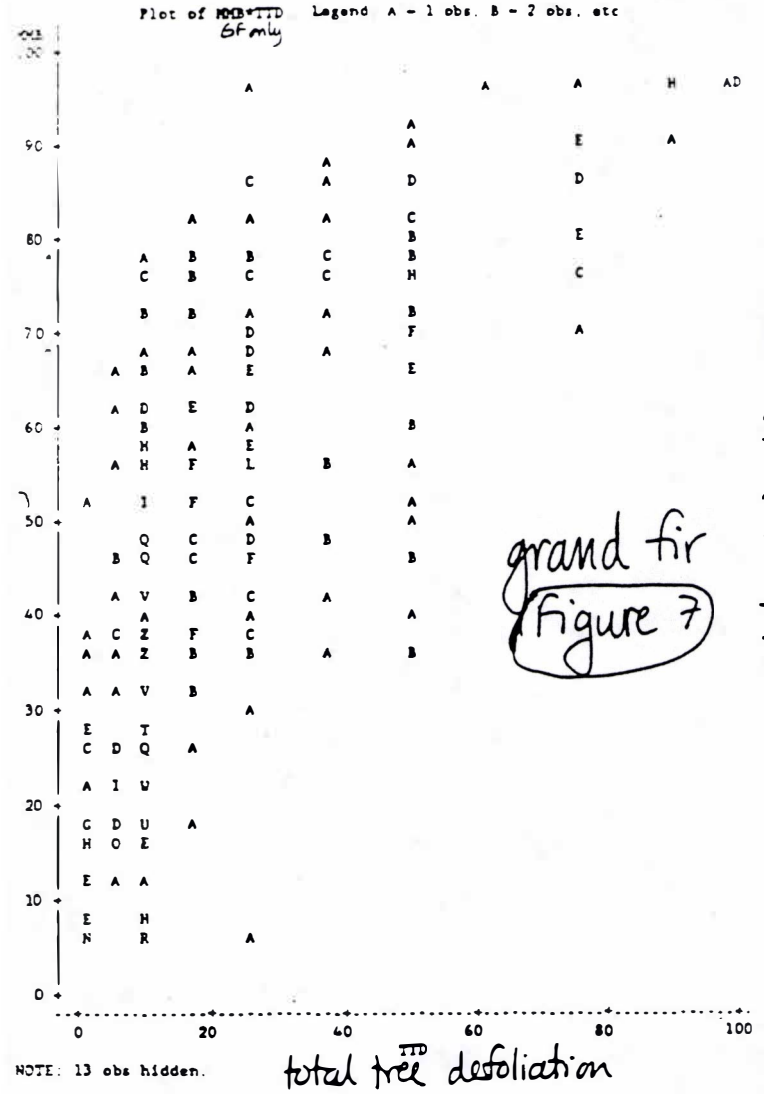



Douglas-fir
Figure 5

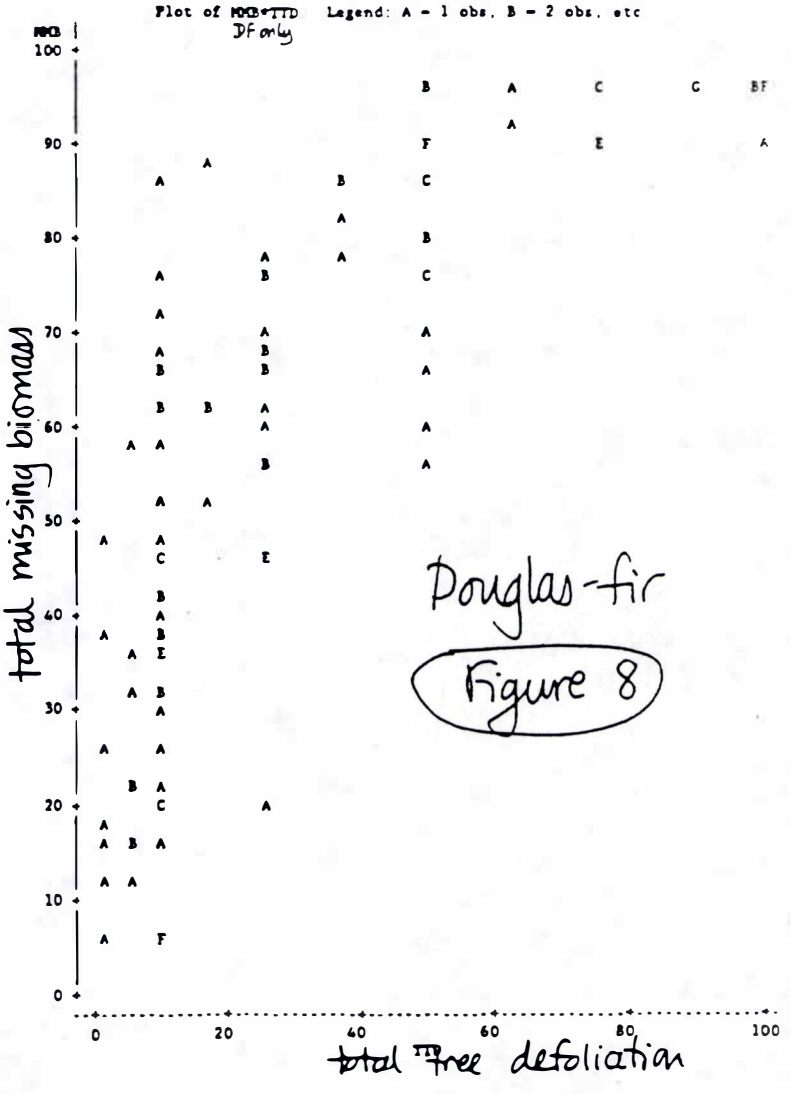



subalpine fir
Figure 6

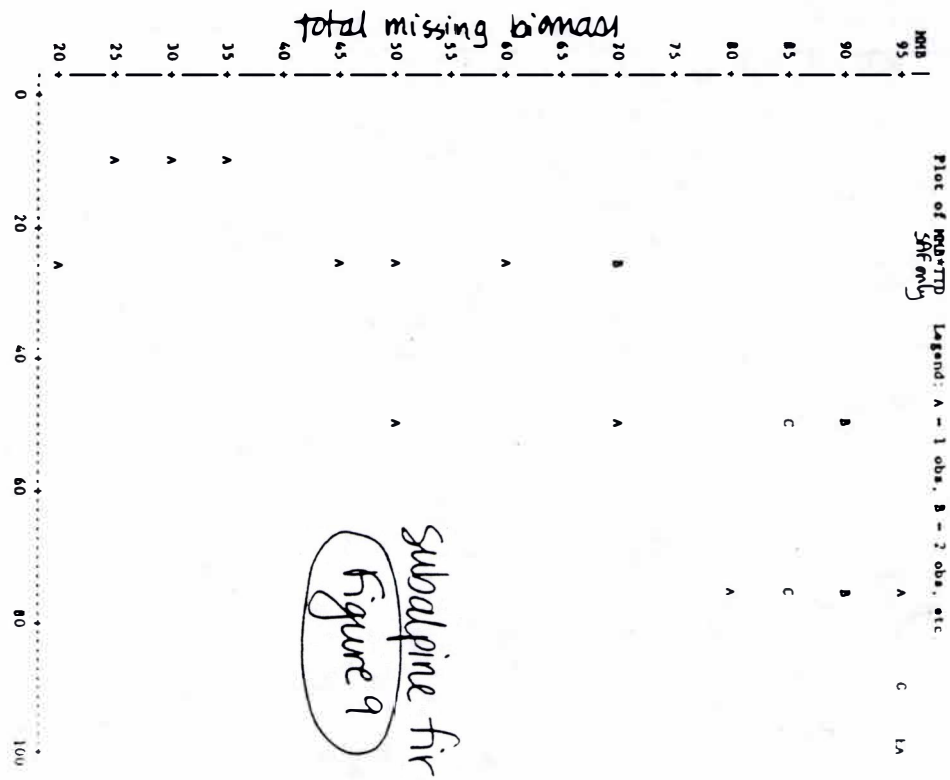
# By Species - Middle Crown 1/3 Only




grand fir
Figure 7



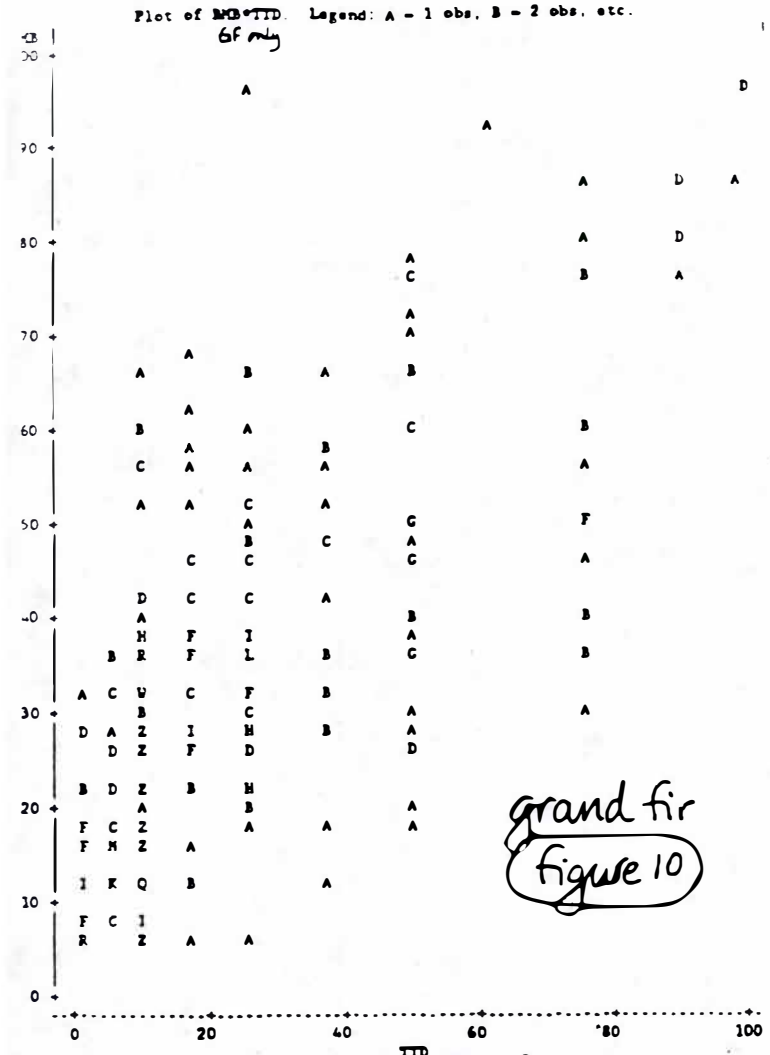

Douglas-fir
Figure 8




Subalpine fir
Figure 9

# By Species - Bottom Crown 1/3 Only

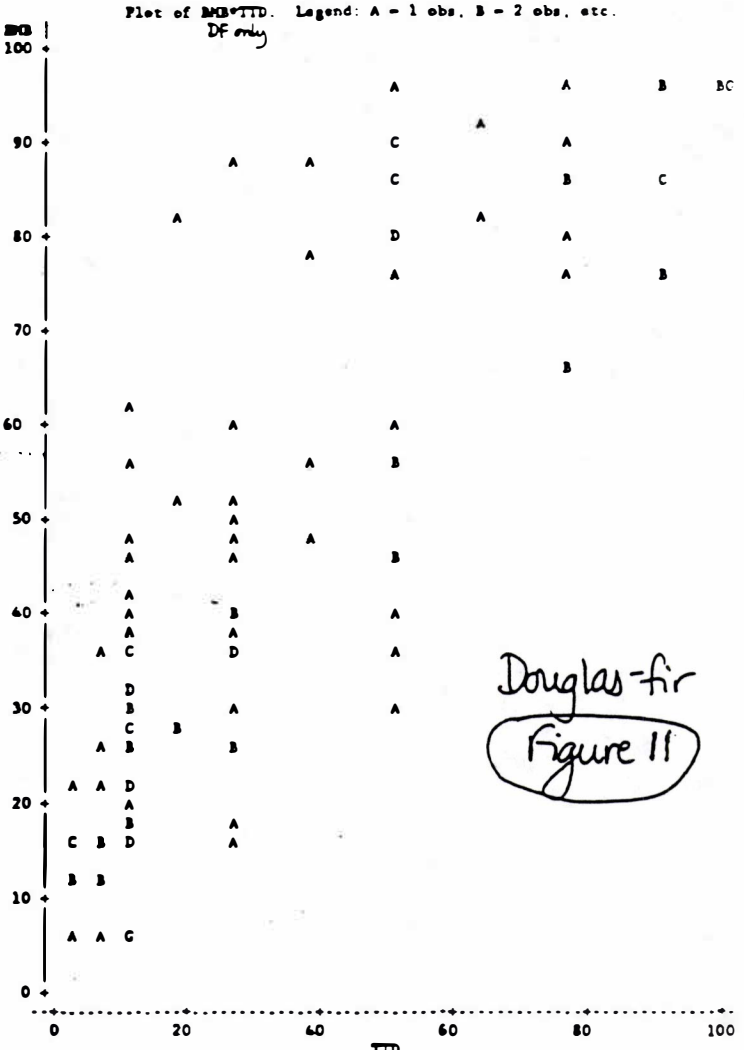





grand fir
Figure 10

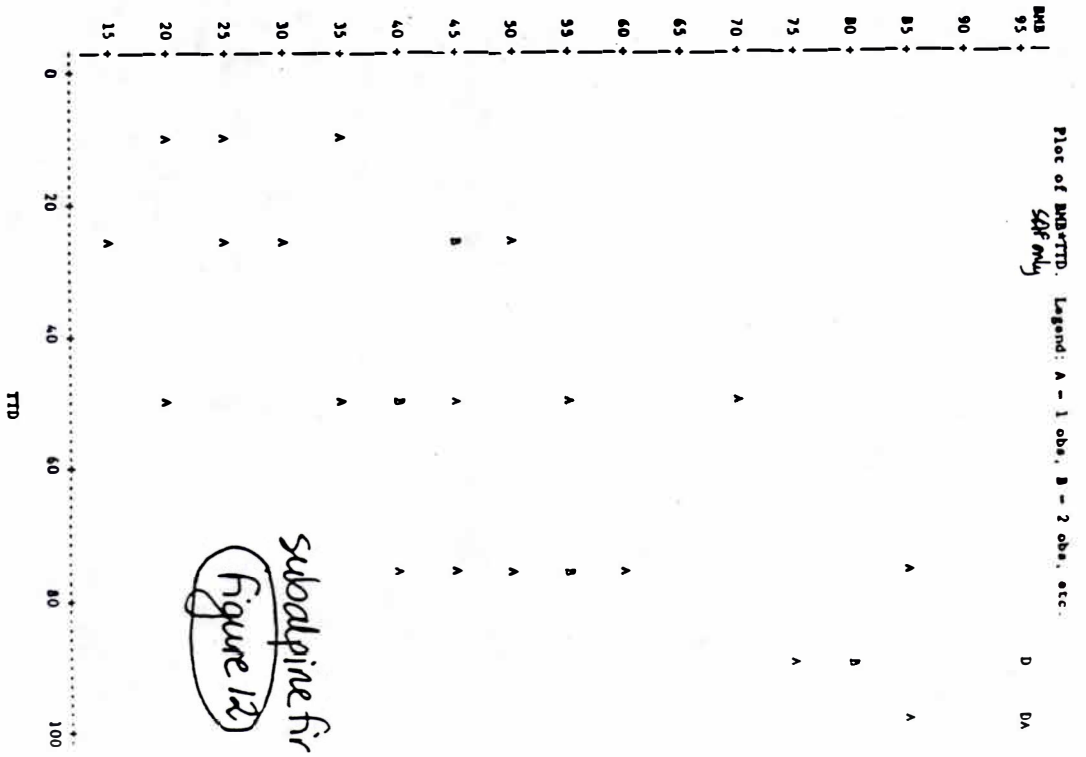
NOTE: 51 obs hidden.

total tree defoliation



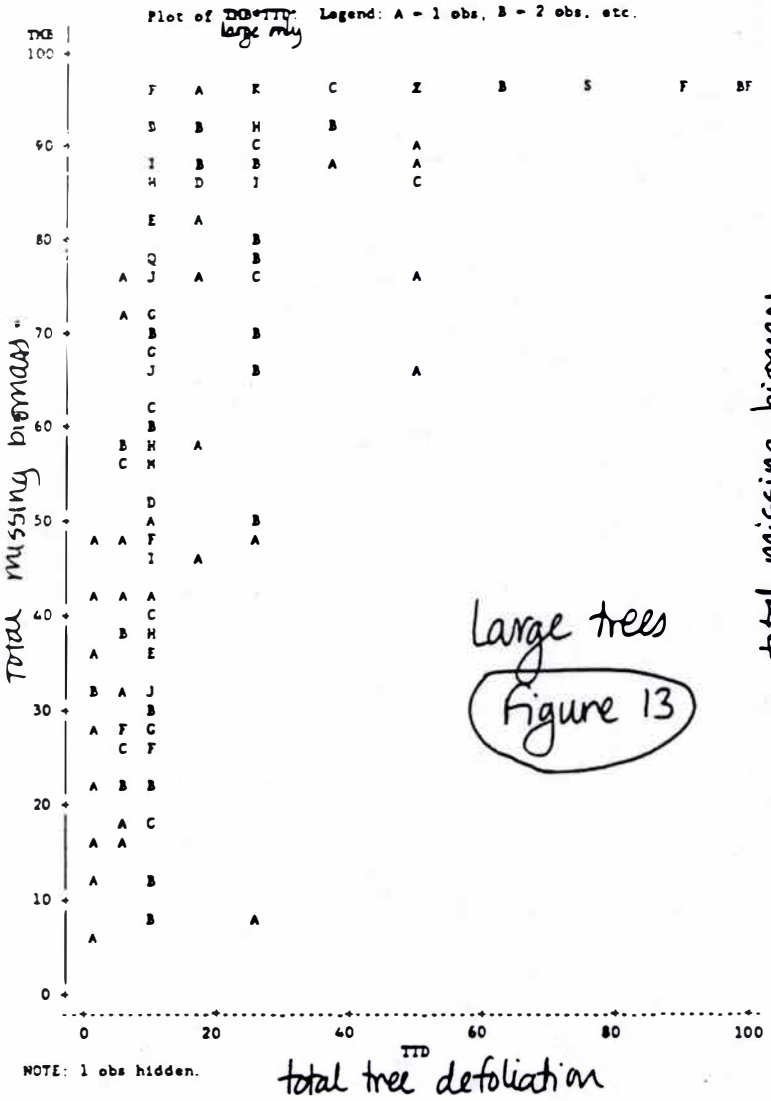

Douglas-fir
Figure 11

total tree defoliation



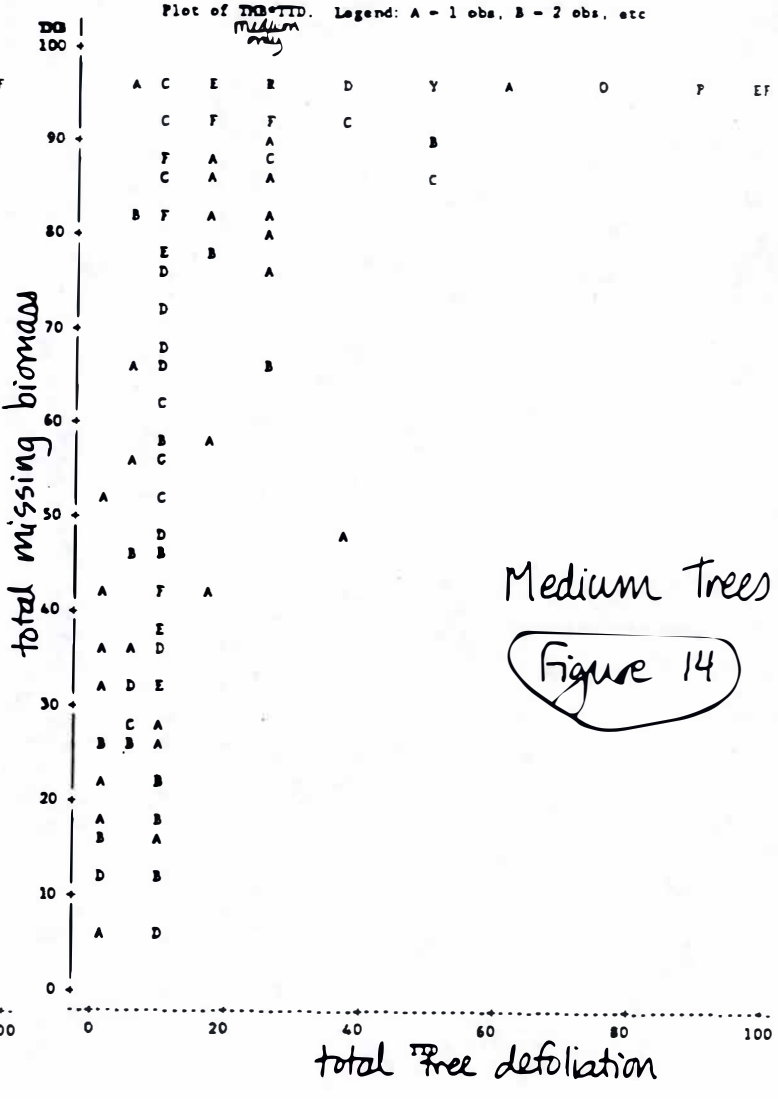

Subalpine fir
Figure 12

# By Size Class - Top Crown 1/3 Only



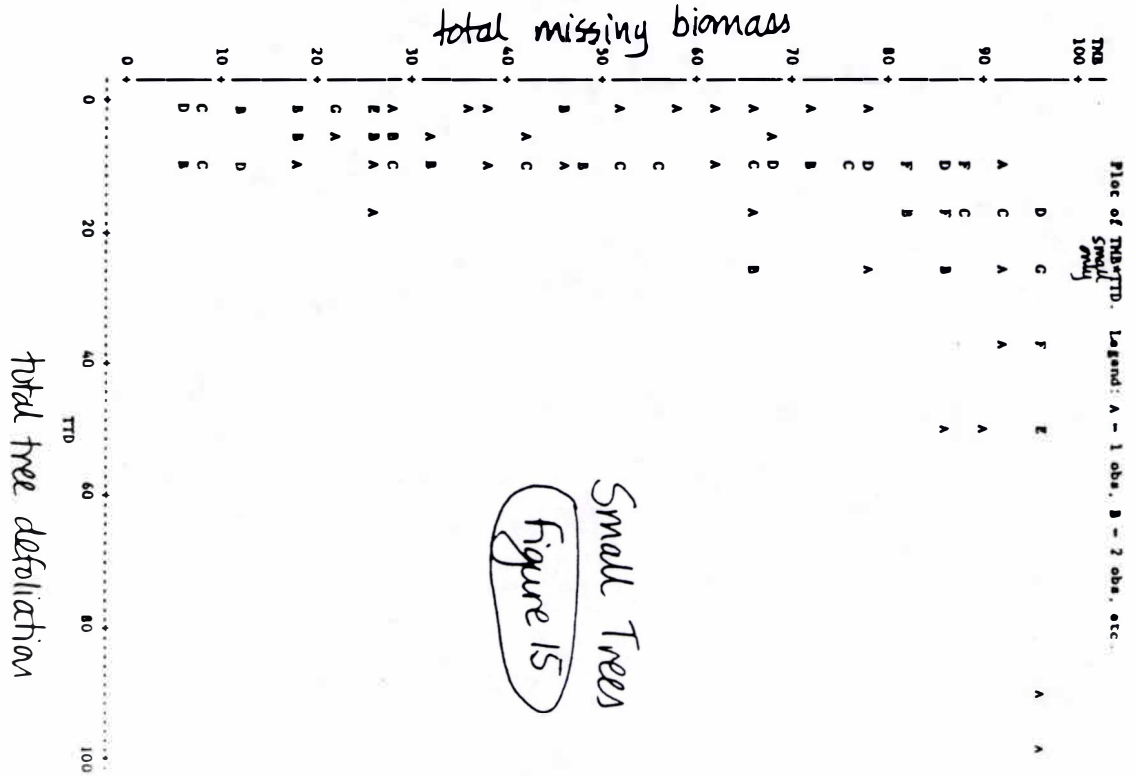

Large trees

Figure 13




Medium Trees

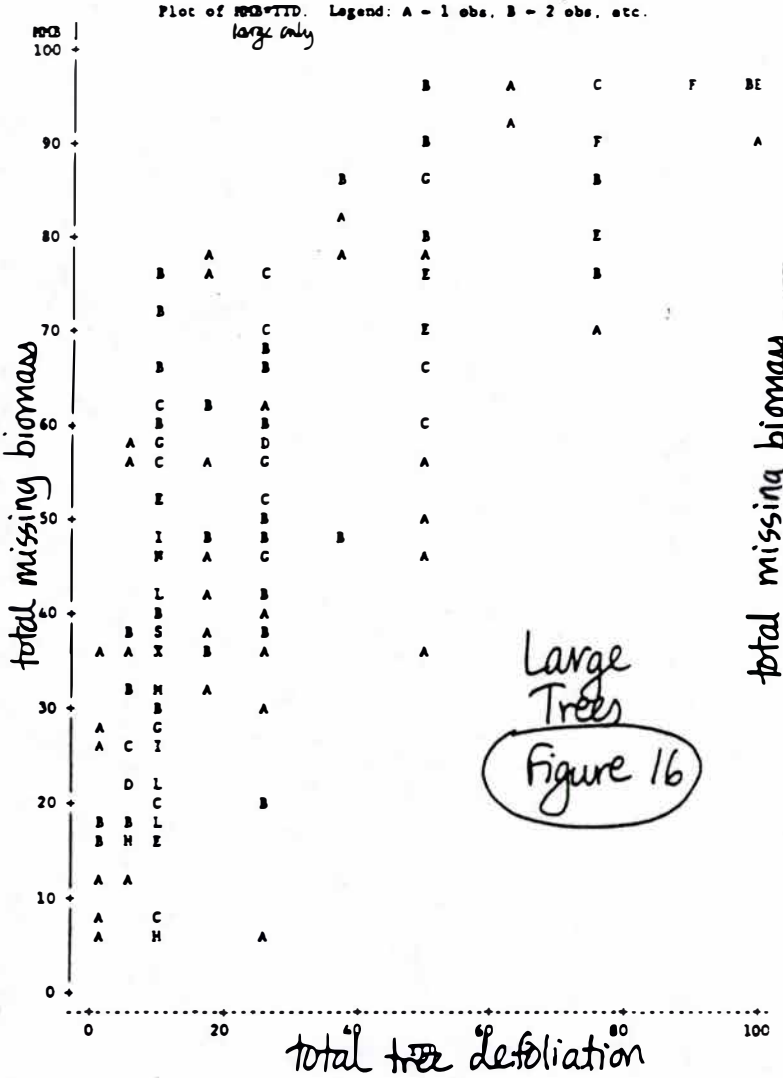
Figure 14



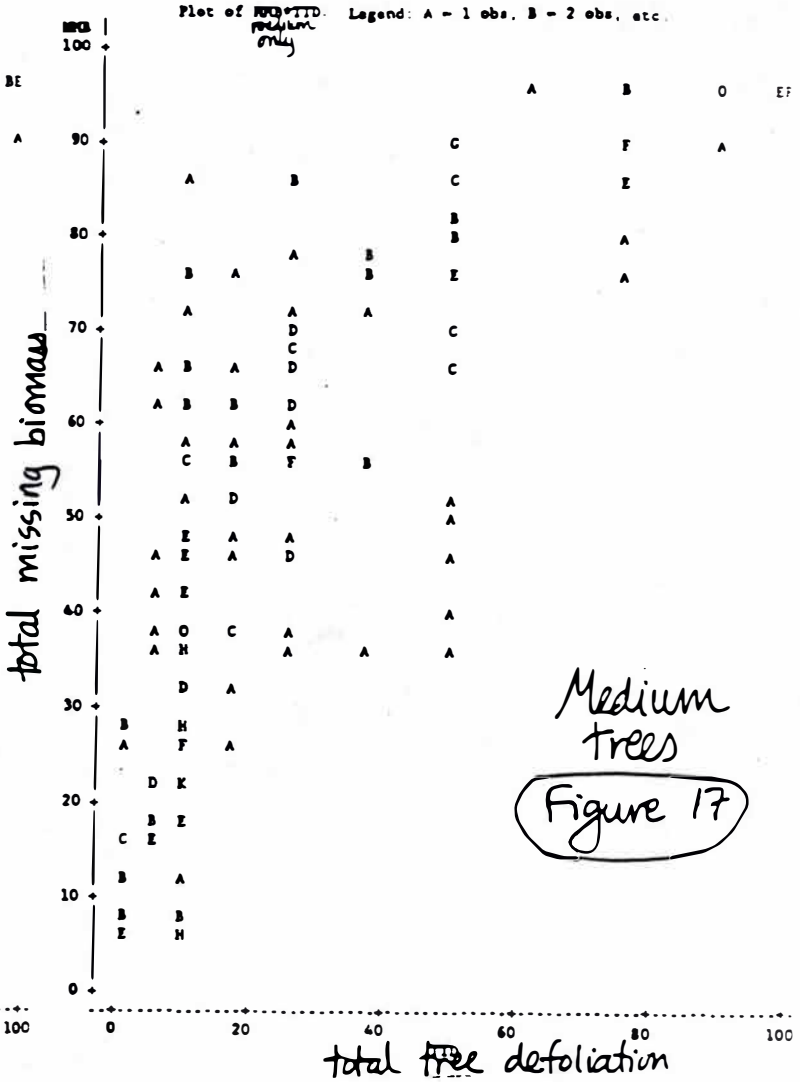

Small Trees

Figure 15

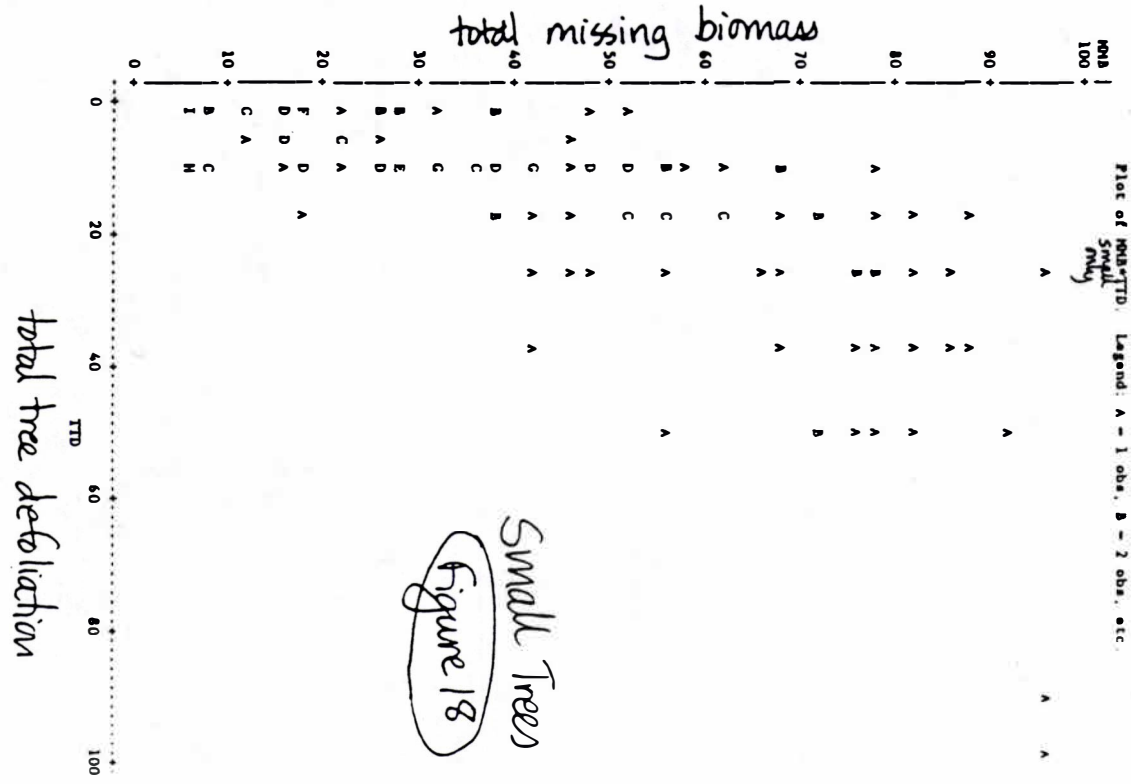
# By Size Class - Middle Crown 1/3 Only




Large Trees
Figure 16

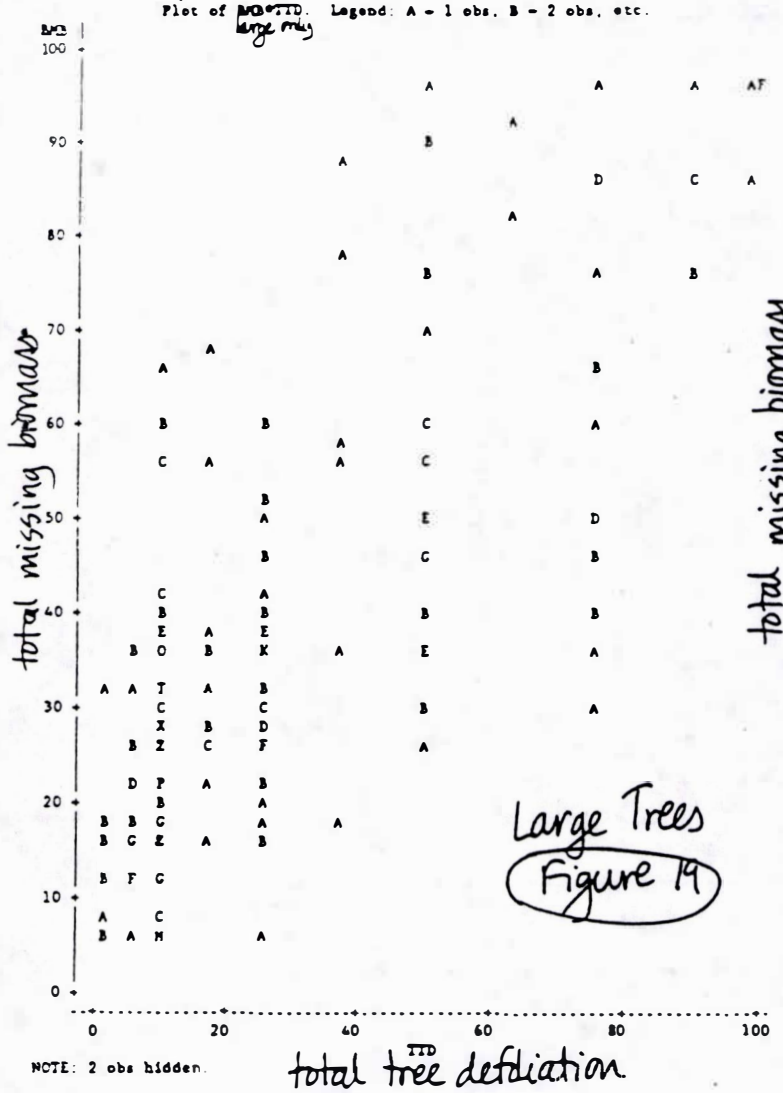



Medium Trees
Figure 17

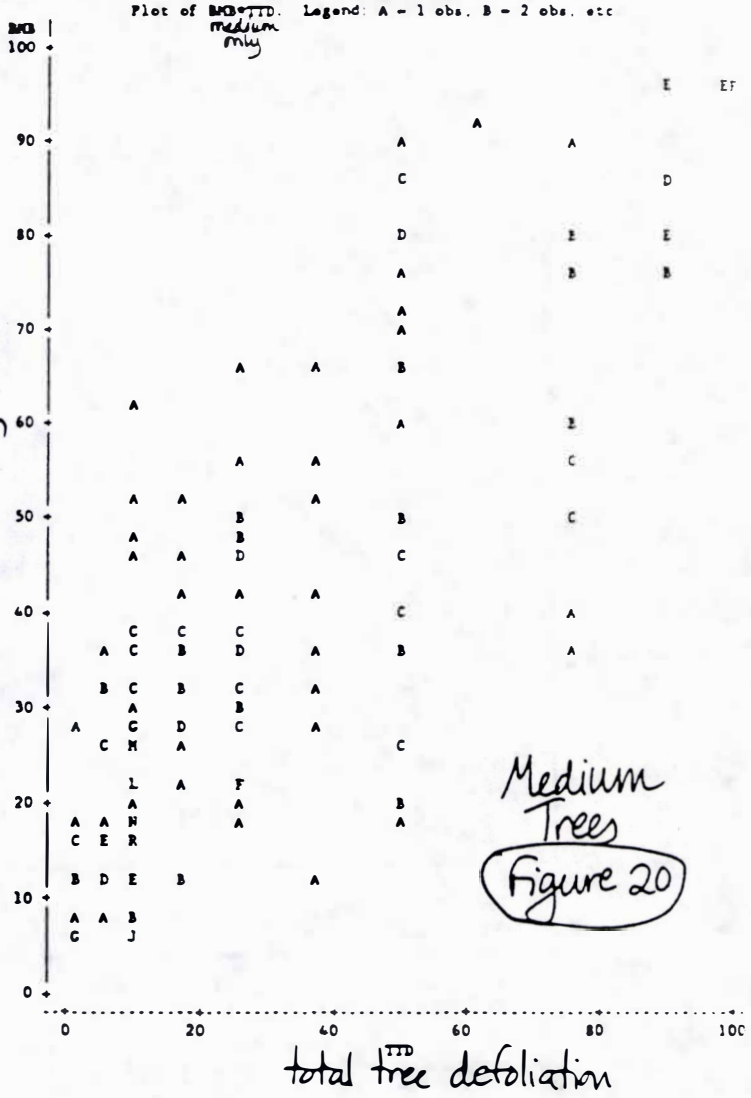



Small Trees
Figure 18

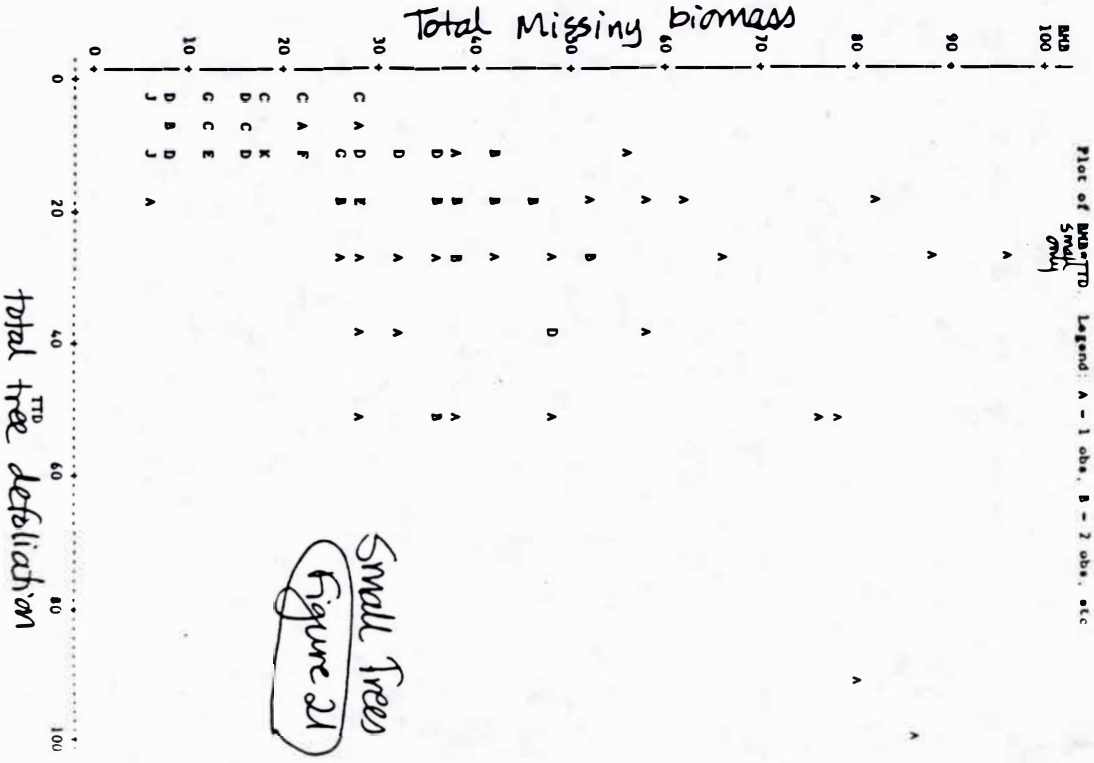
# By Size Class - Bottom Crown 1/3 Only




Large Trees
Figure 19




Medium Trees
Figure 20




Small Trees
Figure 21

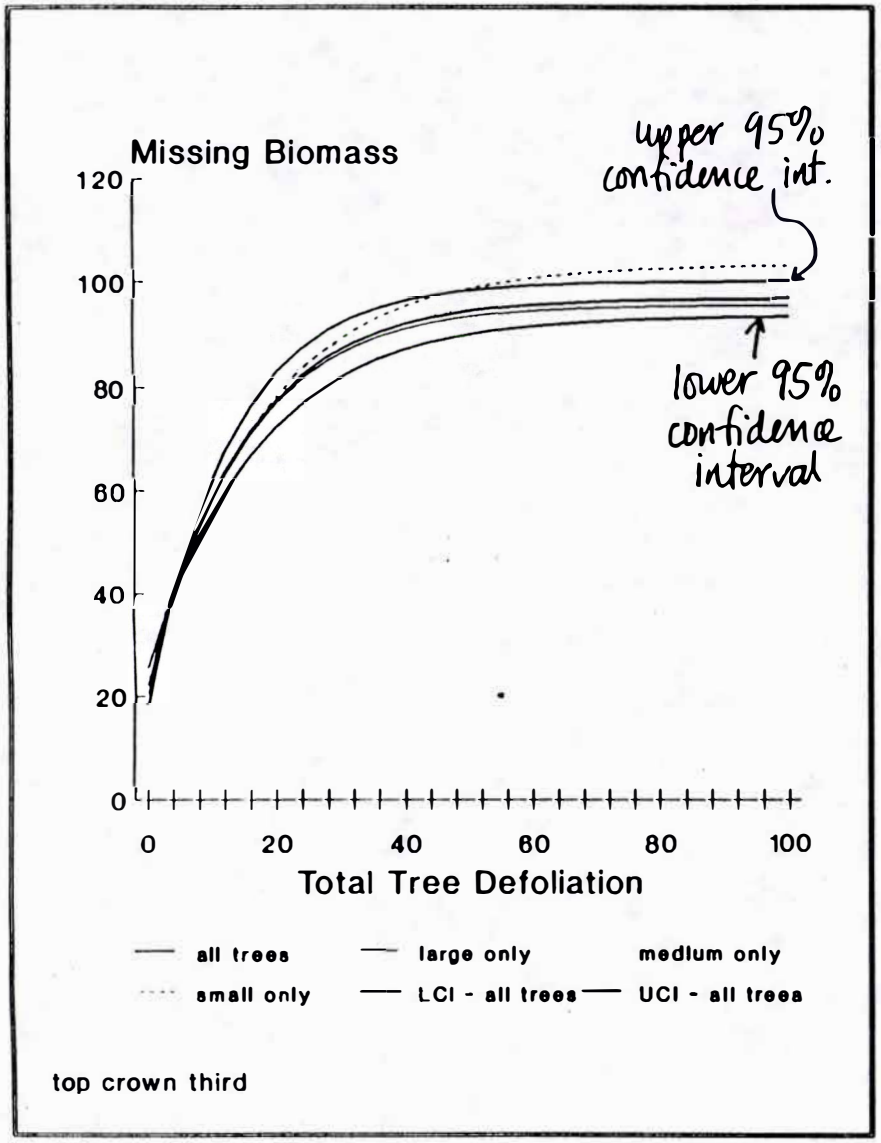



Figure 22

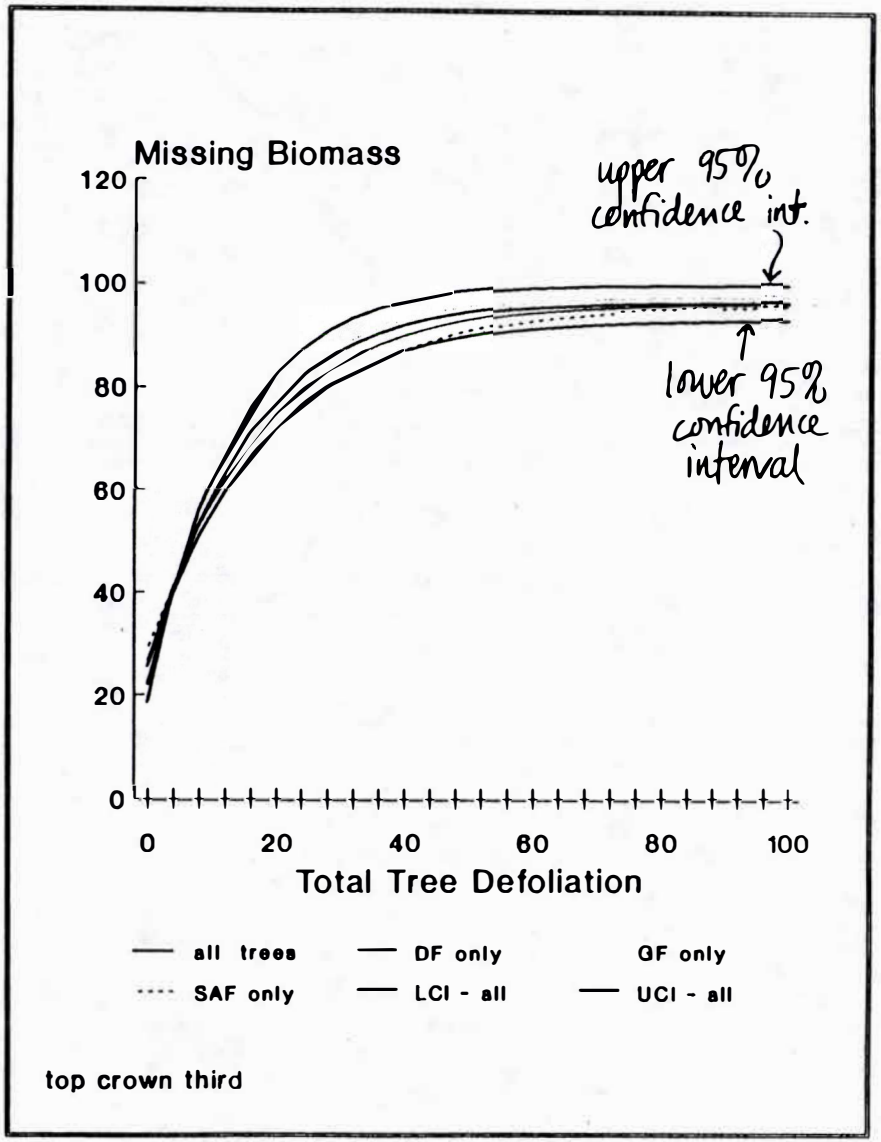



Figure 23

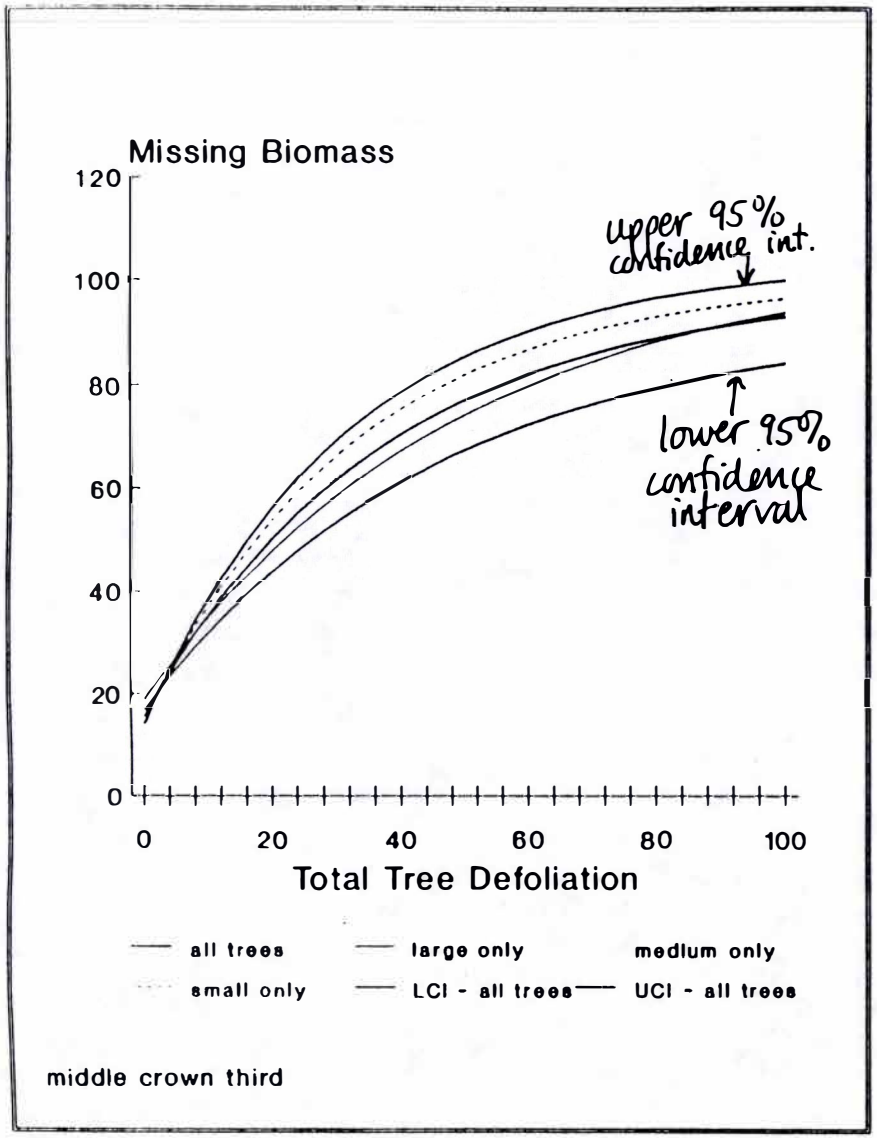



Figure 24

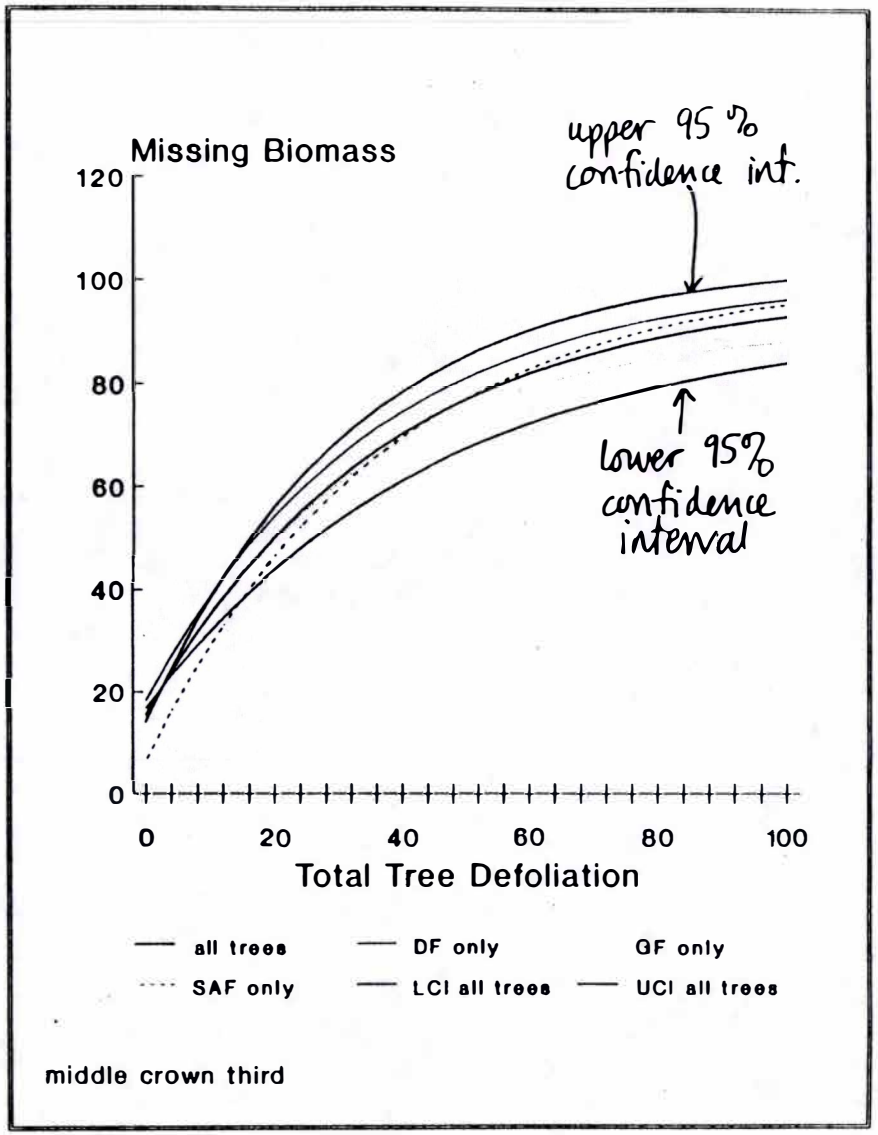
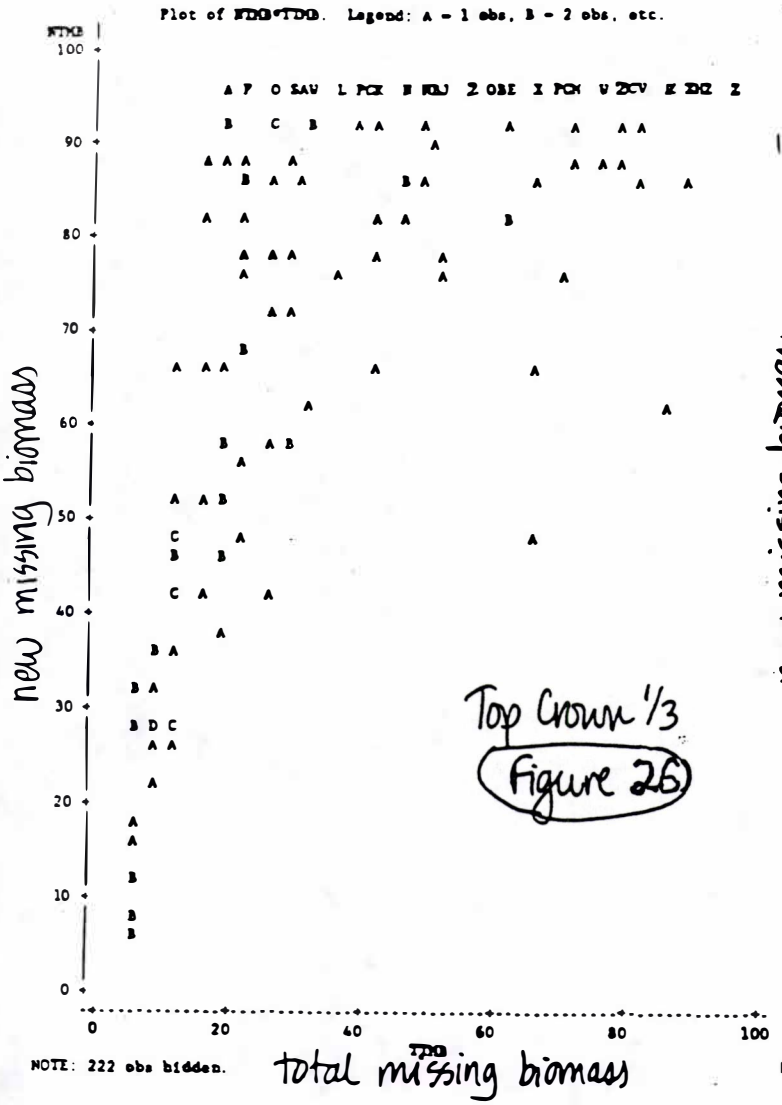



Figure 25

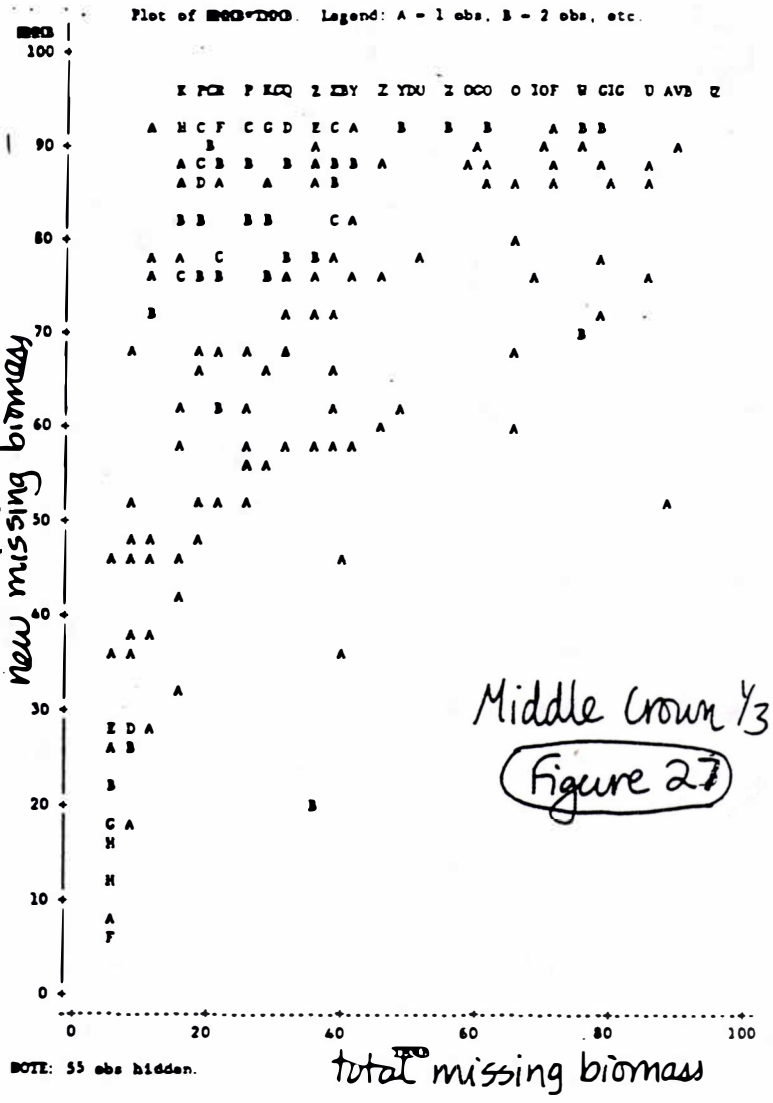
# New vs. Total Missing Biomass





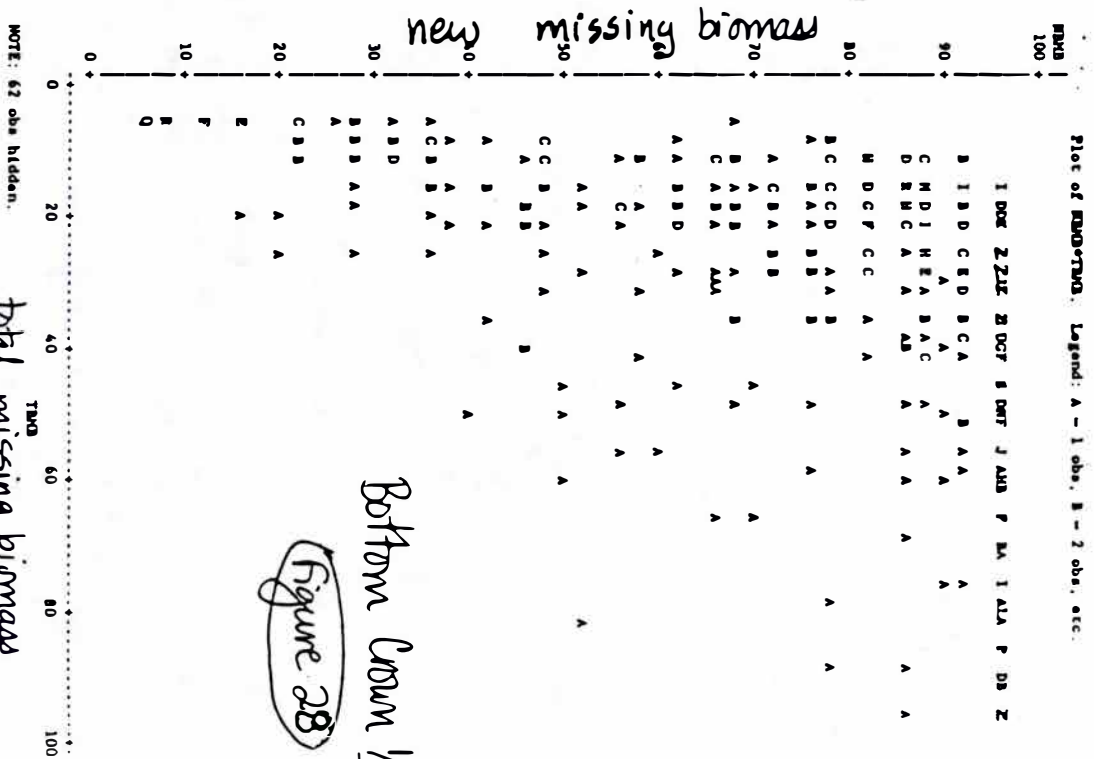

Top Crown 1/3

Figure 26




Middle Crown 1/3

Figure 27




Bottom Crown 1/3

Figure 28